Master's Degree Thesis

Energy engineering

Sizing and scheduling of a microgrid connected to the grid with integration of EV

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Call: July 2017

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ABSTRACT

This project presents a method based on GAMS software, which aim is to determine the optimal size of a microgrid connected to the grid, and the influence of electrical vehicles (EV) in the developing of the investment decision.

The technologies considered in the study are wind turbines, solar panels (PV), batteries, EV and the microgrid can have the possibility to be connected to the grid or not. A sensitivity analysis will be performed in order to check the influence of the weather and of the technologies taken in to account. Finally, an analysis of the optimal scheduling of the system will be presented.

Results show that for this type of system batteries aren't available in any scenario, while electrical vehicles used as batteries can have a very important role for the energy transition. Furthermore it is highlighted the importance to consider as many technologies as possible in order to low total costs of the system.

The simulation is a mixed integer nonlinear programming performed with the solver IPOPT.

KEY WORD: Distributed energy resources, optimization problem, GAMS, EV, microgrid.

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1. INTRODUCTION

i. Motivation

One of the most important challenges of the last years is the energy transition toward renewable and decentralized energies. Renewable energies could face problems like pollution, global warming, dependence of a country from external energy supply, uncertainty of energy's price and potential exposition to global conflicts.

Distributed Energy Resources (DER), especially those based in renewable energies (PV, wind power, hydropower, biomass…), will play a key role in this transition. They will support available capacity to meet demand and they will be the vector for the creation of a new local and decarbonized electrical system.

There are different definitions for a microgrid, DOE's definition (Department Of Energy of United States) [1] says that a microgrid ''is a system in which there is a group of interconnected loads and distributed energy resources (DER) with clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid [and can] connect and disconnect from the grid to enable it to operate in both grid-connected or island mode".

The International Energy Agency (IEA) has estimated that as much as 60% of future electrification in rural households could take place through microgrids and other stand-alone systems (the majority from microgrids) with the balance through grid extension.

Development of microgrids and DER can help to increase the efficiency of the power system, reduce losses at transport and distribution level and allow local network managing. Furthermore they can also offer ancillary services to the grid in the case in which the microgrid could operate a demand-side management or if there's the possibility to store energy, reducing the demand during peak hours and increasing the consumption during valley hours. In this case also the DSO/TSO could invest in this type of systems instead of invest in reinforcing the grid and get important economic and environmental savings. Article 15.8 of the European directive for energy efficiency 2012/27/EU [2] says that:

''*Member States shall ensure that national energy regulatory authorities encourage demand side resources, such as demand response, to participate alongside supply in wholesale and retail markets.*

Subject to technical constraints inherent in managing networks, Member States shall ensure that transmission system operators and distribution system operators, in meeting requirements for balancing and ancillary services, treat demand response providers, including aggregators, in a non-discriminatory manner, on the basis of their technical capabilities.

Subject to technical constraints inherent in managing networks, Member States shall promote access to and participation of demand response in balancing, reserve and other system services markets, inter alia by requiring national energy regulatory authorities or, where their national regulatory systems so require, transmission system operators and distribution system operators in close cooperation with demand service providers and consumers, to define technical modalities for participation in these markets on the basis of the technical requirements of these markets and the capabilities of demand response. Such specifications shall include the participation of aggregators.''

Another problem of these ages are the high levels of pollutants present in the cities due to transportation and the vehicles' noise. A possible solution to these problems is, besides a reduction of private transportation and contemporary a rise of public transportation, the spread of electrical vehicles. By this way, local pollution and noise would be reduced. However, at the moment it would impossible to pass to a full electrical-based transportation model because the grid is not strong enough to support a full electrical vehicle park. For this reason it is important that electrical vehicles are charged in the microgrid, to not overcharge the grid. When they are plugged to the grid, the utilization of smart charger could help alleviating the grid, offering a frequency control.

ii. Objectives

The principal objective of the project is to develop a tool in order to find the optimal size of a microgrid at certain weather and market conditions, investigating the implications that political decisions and resources' availability have in the decision-taking. In the specific the objectives are:

- To implement a program with the software GAMS in order to size a microgrid using historical data for the load and weather conditions;
- To compare the total costs and costs share for different weather conditions;
- To compare at the same weather conditions different technologies in order to check differences in the total costs and in the costs' share of the system;
- To obtain the optimal scheduling of a microgrid under certain conditions;
- To figure out the possible role that EV could have in the smart grid of the future and how they could be used in an optimal scheduling of the system.

iii. Structure

Beyond this initial introduction, the thesis is structured as follow:

CHAPTER 2: State of the art. A literal review about some of the papers that treat about microgrids and virtual power plants. Particular focus on the scheduling of the microgrid and its participation in the electricity market.

CHAPTER 4: Methodology. Input data and variables are listed. Mathematics of the optimization problem are explained and commented. Also there are explained and justified the major assumption done in the problem formulation.

CHAPTER 5: Study case: The microgrid analysed is explained in all its components. A review of the Spanish market framework is presented.

CHAPTER 6: Results. The particular chosen test case for the implementation in GAMS of the model defined in chapter 5 is presented, as well as used parameters. Obtained results are graphically shown and interpreted.

CHAPTER 7: Further improvements. In this section some possible developments of the work are described.

CHAPTER 8: Conclusions. General conclusions and resume of the principal results found during the work.

2. STATE OF THE ART

Penetration of distributed energy resources (DER) is rising fast worldwide, which is mainly associated with the requirement of a sustainable energy system with less environmental problems. When a number of DER units are aggregated, then it is a so-called Virtual Power Plant (VPP). In this construction, the group of DER units will have the same visibility, controllability and market functionality as the conventional transmission-connected power plants [1].

Different definition of VPP are present in the literature, they defined it as a cluster of dispersed generator units, controllable loads and storages systems, aggregated in order to operate as a unique power plant. And they think through the VPP concept, individual DERs can gain access and visibility across all energy markets, and benefit from VPP market intelligence to optimize their position and maximize revenue opportunities. System operation can benefit from optimal use of all available capacity and increased efficiency in operation.

One of the highest priority for microgrids is to keep a reliable power supply to customers instead of economic benefits. In [2] the energy management of a microgrid in grid-connected and stand-alone modes is investigated to find the optimal energy management strategy for these two modes. In the control theory, they take the reliable power supply instead of economic benefits, it maximizes satisfaction rate of load with minimum operation cost in stand-alone mode. They also coordinate controllable units in the long-time period using the schedule layer to optimize microgrid performance and making the best use of intermittent power resources based on forecasting data. This suggests the important role that renewable energy plays in the upcoming microgrid system and how it is dealt with the advantages and drawbacks of this energy.

A comprehensive review of microgrid is done in [3], including the storage system. Their conclusion is that in the future, smart grid infrastructure and energy storage technology will play a significant role, hybrid-energy storage systems are among the most popular research proposals aimed at achieving the goal of smart storage.

The economic scheduling and the optimal management of a renewable micro-grid in an isolated load is a crucial process, where applying the right timing is essential to achieve the correct performance of an energy generation system, such as, wind turbine, solar unit, NG generator and storage battery. [4] Implements a mixed-integer linear programming in General

Algebraic Modelling Systems (GAMS) to reach this optimization. Using a Virtual Power Producer (VPP), they determine the best scenario to minimize the generation cost and optimize the storage charging and discharging time subjected to all operational constraints. The study case was made in the Budapest Tech with their renewable equipment; demonstrates that the method help the planner engineer to minimize the operation cost of the generations units taking into account the reliability expressed in the undelivered energy and using the VPP to control the balance between the generation and consumption hourly during a day.

Also, using GAMS, it was developed a model to optimize the operating strategies and the economic performance of the system, the main goal was to create a system using more local renewable energy which had more reliability of supply, lower the transmission losses and carbon dioxide emissions. The optimization model was applied to a smart microgrid in the Institute of Nuclear Energy in Taiwan. Uncertainty of electricity demand was simulated and sensitivity analysis of battery capacity was conducted. As a result, greater storage capacity requires more investment, which may not be profitable while high fixed cost is considered, optimal battery size should be determined by the demand and the supply of the microgrid, taking in consideration that appropriate battery capacity should be determined by the battery efficiency and power supply [5].

Another interesting solution performed in [6], is to propose a planning methodology in a microgrid to decide optimal locations, sizes and mix of distributed generators. The long-term costs includes investment, operation and maintenance, fuel and emission costs of the distributed generators while maximizing revenue includes payment by microgrid loads and utility grid. The solution is proposed as a min-max-min formulation and cannot be solved directly by using GAMS, a Benders decomposition-type algorithms is the process used to solve this problem. The proposed method takes into account the time-varying load consumptions and intermittent outputs of renewable sources in distributed generation. This uncertainty can be adjusted in a robust optimization and considers the probabilistic nature of planning problem.

As told before, to handle this trend towards a more liberalized electricity market requires more efficient energy management strategies. [7] Describes a market-based Virtual Power Plant model, which provides individual distributed energy resources units to supply the electricity markets. This analysis is recommended to reveal possible impacts in the electricity market when a large number of Market-based Virtual Power Plants are introduced. Two different study case are analysed: the first based on general bidding, the second based on price signal, the conclusion is that the operator of the VPP will be less exposed to risks with a general bidding policy, while the DER's owners are likely to prefer a price signal policy.

The authors of the previous paper, also made an article about designing a Generic Virtual Power Plant (GVPP) model that works under a liberalized electricity market. As the future of distributed energy resources is trending towards a multiple mix of renewables, adapting the existing technologies with the new ones and focusing in not only one Virtual Power Plant technology (VPP), comes as a result of proposing a generic model that meets the different requirements of VPP developers and to be easy to adapt to the individual surroundings [8].

Nerea Ruiz, Iñigo Cobelo and José Oyarzabal wrote a paper [9] about the possibility to reduce the load during specific period of time in a VPP. The algorithm is based on a direct load control with thermostatically controlled appliances. The direct control allow the VPP to optimize its bid in the liberalized electricity market for the load reduction.

Further studies have been performed in order to analyse the possibility for VPP to participate in the day ahead market and in the spinning reserve market. In this case, an optimal bidding strategy is necessary to assure the supply to the load and to optimize the market operations of the VPP [10]. The internal market of a microgrid can be organized in different way at second of the intelligence of the system and the numbers of actors.

3. METHODOLOGY

The purpose of the article is to develop a tool in order to optimize the size of the microgrid's elements when the load, the weather, the market conditions and the cost of the different technologies is an input data.

The technologies taken into account in this work are PV panels, wind turbines, batteries, and electrical vehicles. However, it will be relatively easy to develop the code, increasing the number of technologies taken into account for further improvements.

The objective function of the code that has to be minimized is the difference between total costs and total revenues. The total costs are the sum of the total actualized cost of the system, including operational, investment, maintenance and replacement costs, while revenues are those gains due to the sale of energy to the grid and the savings of oil in conventional vehicles, in the case in which electrical vehicles are in the system. So there haven't been accounted thermal load and associated costs that are an important part of the energy bill.

In eq. 3.1 the objective function to be minimized is represented.

$$BILL= \sum_{y=1}^{y=20}\sum_{d=1}^{d=365}\sum_{t=1}^{t=24}\boldsymbol{Op.costs(t,d,y)} + \sum_{y=0}^{y=20}\big(\boldsymbol{maint.cost(y)} + \boldsymbol{Inv.grid(y)} - \boldsymbol{gain\ oil(Y)}\big) + \boldsymbol{tot.inv.} + \boldsymbol{repl.costs} \tag{3.1}$$

Another contribution of the work is to have built a code that, under specific conditions, allow to optimize the scheduling of the system, minimizing the operational costs and maximizing the profits, if weather and load are available.

It is important to highlight that the results that have been found are conditioned to the fact that the available computers hadn't the capacity to elaborate the quantities of data necessary to size the system, using hourly data of the last twenty years. For this reason, during calculations, have been used data just for 31 days (one month) considering that the generation from renewables, the load and the energy price of this month will be repeated during twenty years. So, all operational costs of that month have been reported to twenty years using the following method: multiplying the cost by twelve, in order to bring the costs from one month to one year and then multiplying the result by 10.1. It's necessary to multiply the operational costs by 10.1 and not by 20 because, due to the interest rate, one dollar spend the 20th year hasn't the same value of one dollar spent the first year.

Different assumptions have been done during the code elaboration. It has been assumed that the energy from the system can be injected into the grid in every moment, without any restriction. Actually, in order to not unbalance the grid, some type of control for this type of system could be required, depending to the legislation and to the size of the plant. Another assumption, in order to sake a greater grade of simplicity is to not have considered power loses in the cables of the microgrid, neither in the transformer and converter. Loses in the single elements are very limited, but summing every type of lose could change something in the results.

Furthermore, any type of restriction on the number of charge/discharge of the batteries hasn't been taken in to account, and neither their consumption. It has been supposed that the batteries will last 10 years, that is a reasonable assumption. Regarding batteries, the self-discharge hasn't been kept into account.

It has been imposed that the electrical vehicles will be unplugged to the grid from 8 to 20, so it's supposed that there is a residential area closed to the complex of office with some EV that are plugged to the grid during the night. During that time they can be used as batteries, while it is considered that for transportation a 20% of EV's battery capacity is used.

During the computation of the total costs, neither the installation of an energy box for the control of the power flow, nor the installation of smart meters for the consumptions' control and a weather forecast station for the forecast of the production haven't been considered. These costs will rise the total expenditure.

The following assumption is about legislation: depending to the country considered, there will be some incentive or taxes for this type of installation. For example in the Spanish market there are some taxes to pay in the case in which a prosumer consume the self-produced energy.

In order to have a more general tool any regulation has been considered, also in order to see the viability of this type of project without any help coming from governmental forces and any type of taxes for the energy sold is considered.

Finally, for simplicity it has been assumed a constant value (1%) for the increase of the power price, the energy and the maintenance costs. It is really complicated to estimate the future value of technologies and services and it wasn't considered in the objectives of the study. However the code is general and open at further improvements or analysis.

i. Sets

In the code there are defined 4 time steps: t0, t (t0), d and y to represent respectively the hours of the day, the number of days in one year and the total number of years considered for the system (20). There are two different time steps for the hours, t0 goes from 0 to 24 while t (to) goes from 1 to 24, because of the batteries' usage it is necessary a continuity function with the purpose to impose that the energy at the last hour of the day is equal to the energy at the first hour of the following day.

ii. Input data

Table 3.1 Data definition and description

Parameter's name	Definition of the parameter
pbg1 (t,d,y)	Solar production of one panel [W].
pbg2	Battery's maximum power of charge [W].
pbg3 (t,d,y)	Wind power production for one turbine [W].
pbg5	Maximum power for a unit of contracted power [W].
pbg6	Maximum power of charge/discharge for an EV's battery [W].
rux	Rump up limit for the x unit [W].
rdx	Rump down limit for the x unit [W].
capacityb	Maximum capacity batteries [Wh].
etabat	Battery efficiency.
EST0	Energy stored in the battery at hour zero of the first year [Wh].
Estmin	Minimum energy stored in the batteries [Wh].
Capacityev	Maximum storage EV [Wh].
EEVT0	Energy stored in the EV's batteries at hour zero of the first year [Wh].
evmin	Minimum energy stored in the EV's battery [Wh].
etaEV	EV's battery efficiency.
Q	Hypothesized energy used for transportation each day from an electrical vehicle [Wh].

lbg5 (t,d,y)	Electricity price from the grid [€/kWh].
pbd1	Maximum power of charge for the battery [W].
pbd2	Maximum power allowed to be injected into the grid [W].
pbd3 (t,d,y)	Load profile [W].
pbd4	Maximum EV's battery charge power [W].
lbd2 (t,d,y)	Energy price of sale to the grid [W].
lbd5	Assumed value for a kWh of energy used by EV for transportation [€/Wh].
Ipv	Investment cost for a PV unit [€].
Iwt	Investment cost for the wind turbine [€].
Ibatt	Investment cost for the battery [€].
Ig	Price for grid unit [€/kW*y].
Iev	Price of EV unit [€].
MANPV	Percentage of the maintenance cost in respect to the investment for PV panels.
MANWP	Percentage of the maintenance cost in respect to the investment for wind turbines.
MANBAT	Percentage of the maintenance cost in respect to the investment for batteries.
MANEV	Percentage of the maintenance cost in respect to the investment for EV.
i	Tax of interest.

iii. Variables

In this section there will be described the variables used in the program. Six different variables are used in order to represent the power generated by the six generators of the system at each hour (PG1, PG2, PG3, PG5 and PG6). Also four different variables are used in order to represent the power demanded at each hour from the four equipment that can absorb power in the system (PD1, PD2, PD3 and PD4).

These variables change in each moment, so they depend to the time, the day and the year in which they are considered.

PG1, PG2, PG3, PG5 and PG6 represent respectively the energy generated by solar panels, batteries, wind turbines and the grid.

PD1, PD2, PD3 and PD4 represent respectively the energy absorbed by the batteries, the grid, the load and by electrical vehicles.

Other variables are that which represent the total costs and gains of the system, that are GG, GO and CG.

GG represents the gains of the grid, it means all the gains of the system due to the sale of energy in each instant.

CG represents the costs of the grid, it means all the costs of the system due to the bought of energy in each instant.

GO represents the gains due to the not usage of conventional fuel. It is an annual cost because the quantity of fuel used each year is considered equal to the fuel that would be used to make the same distance that we could do using the 20 percent of the energy that is present in the electrical vehicle's batteries each day.

Positive variables are used to represent the size of the different equipment. These are the variables that the program has to optimize in order to optimize the bill. These variables are called A, B, C, E and F, that represent respectively the quantity of units of PV panels, wind turbines, batteries, electrical vehicles and kW contracted from the grid.

Other variables represents the fixed costs of the system, so the investment, the maintenance and the replacements costs.

INPV, INWP, INBAT, INEV, INGRID represents respectively the investment to buy solar panels, wind turbines, batteries, electrical vehicles and the grid.

OEMPV, OEMWP, OEMBAT and OEMEV represent the maintenance costs due to solar panels, wind turbines, batteries and electrical vehicles.

REPBAT and REPEV represent the replacement costs for batteries and electrical vehicles, which are the two technologies that need to be replaced during twenty years.

The last variables used in the optimization problem are binary variables, used in order to avoid that the batteries and the grid are used in generation and consumption mode at the same time that would be non-sense from a physical point of view. Six binary variables are used:

U1, U2, U3, W1, W2 and W3, used respectively for the grid, the stationary batteries and the EV batteries.

iv. Constraints

The optimization problem has to satisfy some constraints from a technical point of view.

In equation 3.2 it is represented the produced and absorbed power at each instant which has to be lower than the maximum power available from that source. The maximum power available is given by the power available of a single module multiplied by the factor that represents the optimal size for that equipment. In the case of the wind turbine and of the solar power, the maximum power available is not constant, it depends to the resource in the specific hour.

$$\begin{aligned}
&\mathrm{MATCHED_G1}(t,d,y): \mathrm{PG1}(t,d,y) < A * \mathrm{pbg1};\\
&\mathrm{MATCHED_G2}(t,d,y): \mathrm{PG2}(t,d,y) < B * \mathrm{pbg2};\\
&\mathrm{MATCHED_G3}(t,d,y): \mathrm{PG3}(t,d,y) < C * \mathrm{pbg3}(t,d,y);\\
&\mathrm{MATCHED_G5}(t,d,y): \mathrm{PG5}(t,d,y) < E * \mathrm{pbg5};\\
&\mathrm{MATCHED_G6}(t,d,y): \mathrm{PG6}(t,d,y) < F * \mathrm{pbg6};\\
&\mathrm{MATCHED_D1}(t,d,y): \mathrm{PD1}(t,d,y) < \mathrm{pbd1} * \mathrm{W1}(t,d,y) * B;\\
&\mathrm{MATCHED_D2}(t,d,y): \mathrm{PD2}(t,d,y) < \mathrm{pbd2} * \mathrm{W2}(t,d,y) * E;\\
&\mathrm{MATCHED_D3}(t,d,y): \mathrm{PD3}(t,d,y) = \mathrm{pbd3}(t,d,y);\\
&\mathrm{MATCHED_D4}(t,d,y): \mathrm{PD4}(t,d,y) < \mathrm{pbd4} * \mathrm{W3}(t,d,y) * F;
\end{aligned} \tag{3.2}$$

Furthermore, in the case of the EV, they are available just during some hour, so it is imposed that they can't work during the time in which they are not plugged to the grid (from 8 am to 8 pm). Equation 3.3 represents this constraint.

$$\begin{aligned}
&\mathrm{MATCHED_G6US}(t,d,y):\ \mathrm{PG6}(t,d,y) \mid (t>8) \text{ and } (t<21) = 0;\\
&\mathrm{MATCHED_D4US}(t,d,y):\ \mathrm{PD4}(t,d,y) \mid ((t>8) \text{ and } (t<21)) = 0;
\end{aligned} \tag{3.3}$$

Another physical constraint of the equipment is that the difference of power produced between two time steps has to be lower than the ramp up or ramp down limit of that specific equipment. In the case of time step of an hour there are not technical limitation, but they are included in the code for further improvements.

$$\begin{aligned}
&\text{RAMP_G1}(t0,d,y)\,|\,(t0>1):\ PG1(t0,d,y)-PG1(t0-1,d,y)>-rd1*A;\\
&\text{RAMP_G2}(t0,d,y)\,|\,(t0>1):\ PG2(t0,d,y)-PG2(t0-1,d,y)>-rd2*B;\\
&\text{RAMP_G3}(t0,d,y)\,|\,(t0>1):\ PG3(t0,d,y)-PG3(t0-1,d,y)>-rd3*C;\\
&\text{RAMP_G5}(t0,d,y)\,|\,(t0>1)..\ PG5(t0,d,y)-PG5(t0-1,d,y)>-rd5*E;\\
&\text{RAMP_G6}(t0,d,y)\,|\,(t0>1):\ PG6(t0,d,y)-PG6(t0-1,d,y)>-rd6*F;\\
&\text{RAMP_U1}(t0,d,y)\,|\,(t0)>1):PG1(t0,d,y)-PG1(t0-1,d,y)<\ ru1*A;\\
&\text{RAMP_U2}(t0,d,y)\,|\,(t0>1):\ PG2(t0,d,y)-PG2(t0-1,d,y)<ru2*B;\\
&\text{RAMP_U3}(t0,d,y)\,|\,(t0>1):\ PG3(t0,d,y)-PG3(t0-1,d,y)<ru3*C;\\
&\text{RAMP_U5}(t0,d,y)\,|\,(t0>1):\ PG5(t0,d,y)-PG5(t0-1,d,y)<ru5*E;\\
&\text{RAMP_U6}(t0,d,y)\,|\,(t0>1):\ PG6(t0,d,y)-PG6(t0-1,d,y)<ru6*F;
\end{aligned}\tag{3.4}$$

The power generated from each generator has to be included between the minimum and the maximum available power output. The constraint is represented in equation 3.5.

$$\begin{aligned}
&PGMIN1(t,d,y):\ PG1(t,d,y)>pg1_min\ *U1(t,d,y)*A;\\
&PGMAX1(t,d,y):\ PG1(t,d,y)<pbg1(t,d,y)*U1(t,d,y)*A;\\
&PGMIN2(t,d,y):\ PG2(t,d,y)>pg2_min\ *U2(t,d,y)*B;\\
&PGMAX2(t,d,y):PG2(t,d,y)<pbg2*U2(t,d,y)*B;\\
&PGMIN3(t,d,y):\ PG3(t,d,y)>pg3_min\ *U3(t,d,y)*C;\\
&PGMAX3(t,d,y):\ PG3(t,d,y)<pbg3(t,d,y)*U3(t,d,y)*C;\\
&PGMIN5(t,d,y):\ PG5(t,d,y)>pg5_min\ *U5(t,d,y)*E;\\
&PGMAX5(t,d,y):\ PG5(t,d,y)<pbg5*U5(t,d,y)*E;\\
&PGMIN6(t,d,y):\ PG6(t,d,y)>pg6_min\ *U6(t,d,y)*F;\\
&PGMAX6(t,d,y):\ PG6(t,d,y)<pbg6*U6(t,d,y)*F;
\end{aligned}\tag{3.5}$$

An important principle is the conservation of energy in a closed system, so without keep in to account loses, the total energy generated in an instant t has to be equal to the energy consumed. Equation 3.6 represents the equilibrium between the energy generated and the energy consumed at each time step.

$$\begin{aligned}
&EQ(t,d,y):\\
&\ PG1(t,d,y)+PG2(t,d,y)+PG3(t,d,y)+PG5(t,d,y)+PG6(t,d,y)=\\
&=PD1(t,d,y)+PD2(t,d,y)+PD3(t,d,y)+PD4(t,d,y);
\end{aligned}\tag{3.6}$$

Another constraint is that the batteries can't be charged and discharged and the grid can't sell and buy electricity during the same time step, for this reason binary variables are used in order to respect this constraint.

$$\begin{aligned}&BAT(t,d,y): U2(t,d,y) + W1(t,d,y) < 1;\\&GRID(t,d,y):\ U5(t,d,y) + W2(t,d,y) < 1;\\&EV(t,d,y):\ U6(t,d,y) + W3(t,d,y) < 1;\end{aligned} \quad \textbf{(3.7)}$$

A particular attention has to be used for batteries. The first needed additional constraint is the control of the state of charge in each moment. In the case of stationary batteries the equation is valid for all the hours. Equation 3.8 impose that energy inside batteries is equal to the energy present in the batteries during the previous hour minus the energy generated by the batteries, or plus the energy absorbed by the batteries, keeping into account the efficiencies of charge/discharge.

$$\begin{aligned}&EBAT(t0,d,y) \mid (t0 > 1):\ EST(t0,d,y) =\\&= EST(t0-1,d,y) - PG2(t0,d,y)/etabat + PD1(t0,d,y) * etabat;\end{aligned} \quad \textbf{(3.8)}$$

While for electrical vehicles’ batteries the equation is valid just for the hours in which they are plugged to the grid. At the hour in which vehicles return to be plugged to the grid they will have a SOC equal to the SOC at the hour in which they left the system minus the charge used for transportation (supposed to be the 20 percent of the total charge). See equation 3.9.

$$\begin{aligned}&EEV18(t0,d,y) \mid ((t0 > 1) \text{ and } (t0 < 9)):\ EEVT(t0,d,y) =\\&= EEVT(t0-1,d,y) - PG6(t0,d,y)/etaEV + PD4(t0,d,y) * etaEV;\\&EEV820(t0,d,y) \mid (t0 = 20):\ EEVT(t0,d,y) = EEVT(t0-12,d,y) - ETR;\\&EEV2024(t0,d,y) \mid (t0 > 21):\ EEVT(t0,d,y) =\\&= EEVT(t0-1,d,y) - PG6(t0,d,y)/etaEV + PD4(t0,d,y) * etaEV;\end{aligned} \quad \textbf{(3.9)}$$

Another important constraint is the condition that impose the level of charge of the batteries at the first hour of the first year that is equal at the 59 percent of the capacity of one battery multiplied by the number of batteries in the system.

$$\begin{aligned}&EBAT1(t0,d,y) \mid (t0 = 1) \text{ and } (d = 1) \text{ and } (y = 1)):\ EST(t0,d,y) = EST0 * B;\\&EEV1(t0,d,y) \mid ((t0 = 1) \text{ and } (d = 1) \text{ and } (y = 1)):\ EVT(t0,d,y) = e = EEVT0 * F;\end{aligned} \quad \textbf{(3.10)}$$

It's important to impose that the SOC of batteries at the last hour of the day is equal the SOC of the following day, this is a continuity equation (equation number 3.11).

$$\begin{aligned}&BATCONT(t0,d,y) \mid ((t0 = 1) \text{ and } (d > 1)):\ EST(t0,d,y) = EST(t0+24,d-1,y);\\&EVCONT(t0,d,y) \mid ((t0 = 1) \text{ and } (d > 1)\ \text{ and}(y > 1):\ EEVT(t0,d,y) = EEVT(t0+24,d-1,y);\end{aligned} \quad \textbf{(3.11)}$$

The last constraint for the batteries is that they can't never overpass the minimum (40 percent of the capacity) and the maximum capacity.

$$\begin{aligned}
&\mathrm{DISCH(t0, d, y) \mid (t0 > 2): \ PG2(t0, d, y) < EST(t0 - 1, d, y) - estmin * B;}\\
&\mathrm{CH(t0, d, y) \mid (t0 > 2): \ PD1(t0, d, y) < capacityb * B - EST(t0 - 1, d, y);}\\
&\mathrm{MINEV(t0, d, y) \mid (t0 > 2): \ PG6(t0, d, y) < EEVT(t0 - 1, d, y) - evmin * F;}\\
&\mathrm{MAXEV(t0, d, y) \mid (t0 > 2): \ PD4(t0, d, y) < capacityev * F - EEVT(t0 - 1, d, y);}
\end{aligned} \tag{3.12}$$

Equation 3.13 imposes an additional constraint for EV. It imposes that the level of charge at 8 am has to be higher than the minimum level of charge plus the energy that they will use for transportation.

$$\mathrm{MINEV8(t0, d, y) \mid (t0 = 8): \ EEVT(t0, d, y) > evmin * F + ETR;} \tag{3.13}$$

v. Objective function

The objective function that has to be minimized is the sum of the total cost, given by the sum of the operational, investment, maintenance and replacement costs minus the gains due to the injection of energy into the grid and the savings of the oil in conventional vehicles.

$$\begin{aligned}
&\mathrm{OF: \ BILL} = ((\sum_{y=0}^{y=20} \sum_{d=1}^{d=365} \sum_{t=0}^{t=24} \mathrm{TOC(t, d, y)}) + \\
&\sum_{y=0}^{y=20} (\mathrm{OEMTOT(y) + INGRID(y) - GO(y)}) + +\mathrm{TOTINV + TOTREP});
\end{aligned} \tag{3.14}$$

In the objective equation appear some fixed terms and some variable terms that change each hour.

TOC represents the total operational costs and it is the sum of the costs of the grid and the gains due to the sale of the electricity, CG and GG respectively, and it is represented in the equation 3.15.

$$\mathrm{TOTOPCOST(t, d, y): \ TOC(t, d, y) = CG(t, d, y) + GG(t, d, y);} \tag{3.15}$$

CG and GG are calculated multiplying the quantity of energy used or sold in that hour by the price at that hour. Furthermore, the different costs are calculated keeping into account the interest tax in order to actualize the cost at the first year, and the rise of the price during the time (1 percent a year).

The price of the cost grid is divided by 10^3 because the price is given in €/kWh, while the other terms are in €/MWh.

$$\begin{aligned}&\mathrm{COSTGRID(t, d, y): CG(t, d, y) =}\\&\mathrm{= (PG5(t, d, y) * Ibg5(t, d, y)/1000) * ((100 + (y/100))/((1 + i)^\wedge y));}\end{aligned} \quad \textbf{(3.16)}$$

The price of the gain grid is divided by 10^6 because the price is given in €/MWh.

$$\begin{aligned}&\mathrm{GAINGRID(t, d, y): GG(t, d, y) =}\\&\mathrm{= (PD2(t, d, y) * Ibd2(t, d, y)/1000000) * ((100 + (y/100))/((1 + i)^\wedge y));}\end{aligned} \quad \textbf{(3.17)}$$

GO is a fixed term that represents the saving of oil in conventional vehicles, it is calculated assuming that the vehicles will use on average a 20 percent of the total capacity, and assuming a price for the oil that will increase of one percent a year. This is an annual term, so it represents the total savings of one year due to the not usage of conventional vehicles.

$$\mathrm{GAINOIL(y): GO(y) = ETR * Ibd5 * 365 * ((100 + (y/100))/((1 + i)^\wedge y));} \quad \textbf{(3.18)}$$

Also the investment cost for PV panels, batteries, wind turbines, power contracted from the grid and electrical vehicles are keep in to account. They are calculated multiplying the cost of a single unit, e.g. a solar panel, by a factor that will represents the size of each component, represented in 3.20. Equation 3.19 represents the total cost, the sum of these investments.

$$\mathrm{TOTALCOST: TOTINV = INPV + INBAT + INWP + INEV;} \quad \textbf{(3.19)}$$

$$\begin{aligned}&\mathrm{COSTPV: INPV = A * Ipv;}\\&\mathrm{COSTBAT: INBAT = B * Ibact;}\\&\mathrm{COSTWP: INWP = C * Iwt;}\\&\mathrm{COSTEV: INEV = F * Iev;}\end{aligned} \quad \textbf{(3.20)}$$

In the case of the grid there is a difference respect to the other type of investments because it has to be renovated each year. So it is necessary to keep into account the interest tax and the increase of the price for the contracted power during that time.

$$\mathrm{COSTGR(y): INGRID(y) = Ig * E * ((100 + (y/100))/((1 + i)^\wedge y));} \quad \textbf{(3.21)}$$

Another important term to keep into account is the total maintenance cost of the system, represented with the equation TOTMANT that is the sum of the maintenance cost for PV panels, wind turbine, batteries and electrical vehicles.

$$TOTMANT(Y): OEMTOT(Y) = OEMPV(y) + OEMWP(Y) + OEMBAT(Y) + OEMEV(y) \quad \textbf{(3.22)}$$

They are assumed to be the five percent of the investment cost. Also in this case, it is an annual cost so it is needed to keep in to account the interest tax and the increase in the price. It is formulated in equation 3.23.

$$\begin{aligned}
&\text{MANTPV(y): OEMPV(y)} = \text{INPV} * \text{MANPV} * ((100 + (\text{y}/100))/((1+\text{i})\text{\^{} y}));\\
&\text{MANTWP(y): OEMWP(y)} = \text{INWP} * \text{MANWP} * ((100 + (\text{y}/100))/((1+\text{i})\text{\^{} y}));\\
&\text{MANTBAT(y): OEMBAT(y)} = \text{INBAT} * \text{MANBAT} * ((100 + (\text{y}/100))/((1+\text{i})\text{\^{} y}));\\
&\text{MANTEV(y): OEMEV(y)} = \text{INEV} * \text{MANEV} * ((100 + (\text{y}/100))/((1+\text{i})\text{\^{} y}));
\end{aligned} \quad \textbf{(3.23)}$$

The last term that is kept in to account are the replacement costs for that equipment that have a shorter life than twenty years, so they will have to be substituted during the life time of the system. These equipment are the batteries and the electrical vehicles, that have a useful life of 10 ten years.

The equations for the replacement is equation 3.24, while the total replacement costs are represented in 3.25.

$$\begin{aligned}
&\text{REPLACEMENTBAT: REPBAT} = \text{INBAT}/((1+\text{i})\text{\^{}10});\\
&\text{REPLACEMENTEV: REPEV} = (\text{INEV}/((1+\text{i})\text{\^{}10});
\end{aligned} \quad \textbf{(3.24)}$$

$$\text{TOTREPLACEMENT: TOTREP} = \text{REPBAT} + \text{REPEV}; \quad \textbf{(3.25)}$$

4. STUDY CASE

i. Description of the microgrid

For definition, a microgrid is “A group of interconnected loads and distributed energy resources (DER) with clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid [and can] connect and disconnect from the grid to enable it to operate in both grid-connected or island mode.” In Figure 4.1, an example of microgrid is represented. [11]

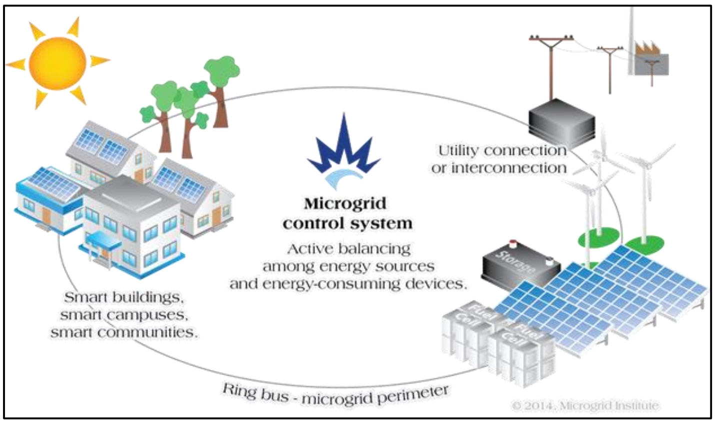

Figure 4.1 Example of a microgrid

They can be developed for a small community, an office complex, universities and they meet the same needs as if they would have been connected directly to the larger grid. Microgrids offers big vantages for the consumers and for the whole system. Consumers will have more independence from the fluctuation of prices in the energy market, and there is the possibility to save money if the sizing is optimized. For the whole system the advantages are a reduction of loses, because the energy produced is consumed very closed to the generator, microgrids can also participate in the reduction of the peak load thanks to the storage system and the controllability of the load, so less investments in order to reinforce the grid are necessary.

There are also some disadvantages in the construction of a microgrid, for examples the high initial costs and some problem that could create the bi-directional flow of power in the grid, it means some additional costs.

In this case the load is well defined, and it is considered just the electrical load, without keep in consideration the thermal load. It is supposed to be a group of offices with a similar consumption profile (higher during the day, lower during the night and week-end).

The production from DER comes from a mix between PV panels and wind turbine. They will be little installation on roofs and distributed along the whole area of the microgrid in order to avoid unpleasant vision about big production plant.

In addition, the microgrid will have a control centre for the data storage and for the energy storage. The data centre is needed to aggregate information about consumption, production, state of charge of the batteries and coordinate operations, optimizing the scheduling of the system basing on production, demand and price forecast.

This microgrid will work connected to the grid and there will be just a contract for all the consumers. In order to share the costs of the system, each consumer will have a smart meter used for the calculation of the real consumption of each building.

Definition of the load

The load is an office complex, the consumption is lower during week-ends and also during nights. Data have been taken from the software EnergyLens that simulate consumptions with time steps of one hour.

The peak load is 1,078 kW, while the total energy average consumed during the whole day is 9.2 MWh/d. In Figure 4.2 it is represented the daily consumption profile during a week day in January.

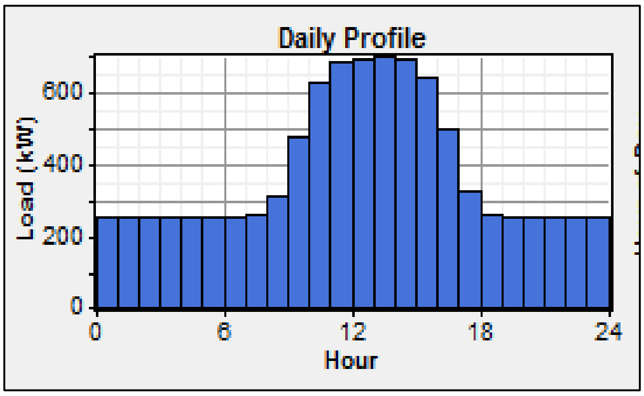

Figure 4.2 typical daily profile of the load

PV and wind power production

The Energy production from PV has been calculated using HOMER software. Threw HOMER it is possible to import Excel files, giving hourly values for radiation (from the

Girona airport). Furthermore, data about efficiency and type of PV panel installed can be used in the program, which could give a quite accurate value of the energy output.

Also in the case of the wind speed, data from the Girona airport have been used. In this case an Excel program has been developed in order to simulate the behaviour of the wind turbine installed at given wind speed. In Figure 4.3 and 4.4 it is represented the real power curve and the simulated power curve.

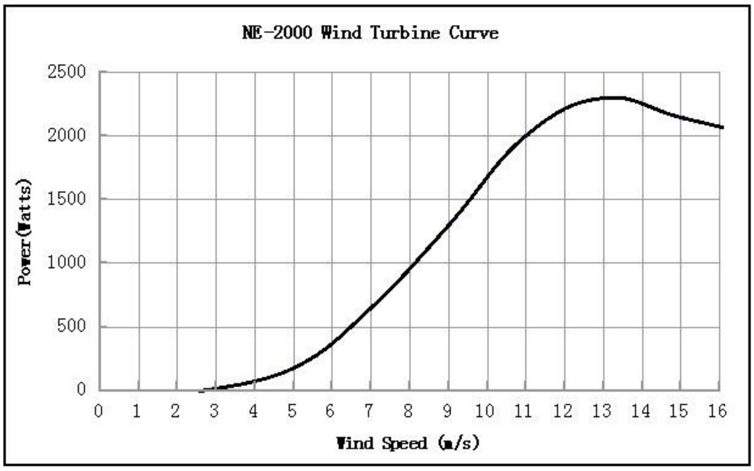

Figure 4.3 Real power curve wind turbine

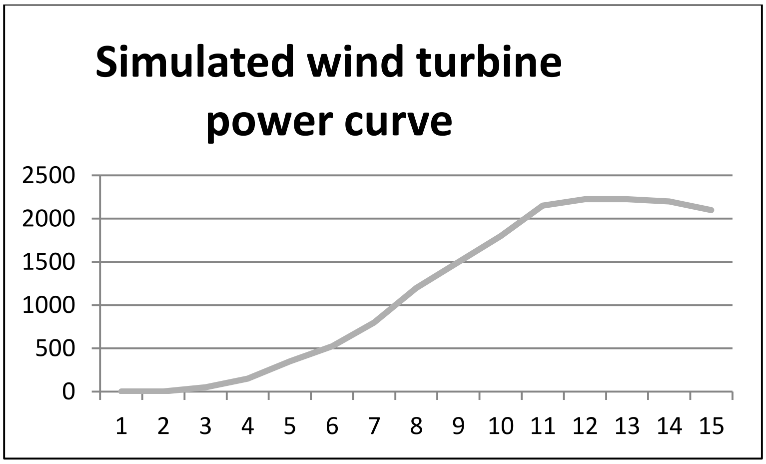

Figure 4.4 Simulated power curve wind turbine

Technologies and costs

In this section there will be listed all technologies considered, describing the principal characteristics and costs.

- **EV:** The model used is a Mitsubishi IMiEV, with 24 KWh battery, 6.6 kW when charging, and an efficiency of 0.89 when charging and when discharging. The price is 23000 €. In the program the investment cost is supposed to be 10000 € because this electric car is used instead than a conventional vehicle, that would be bought in any case [13] [14];

- **PV:** The model selected is an YCPV-260P, with a size of 1640*992*40 mm. The nominal power is 260 W, the efficiency is 0.1598 and the temperature coefficient is -0.42 %/C. The investment cost for a single module is supposed to be 230 €/module [15];

- **Wind turbine:** The model selected is a NE-2000, with a rated power of 2 kW and a maximum power of 2300 W. It is a horizontal axis wind turbine and the cost of one module is about 2000 €/module [16];

- **Battery:** The model selected is an UP-GC16-6RE, with a rated power of 300 W, the capacity is 6600 Wh and an efficiency of 0.92. It is a lead-acid battery, perfect for this kind of appliances. The price of one battery is 700 €, and the useful life is about ten years. So it is supposed to change the batteries one time during the life cycle of the project (20 years) [17].

ii. Market regulation and framework

Due to the strategic role that management of energy services has in a country, in Spain it has been thought as a governmental competence. At the final of the 20th century, in order to improve competitiveness and efficiency of the system, a liberalization of the market has been done. So a transformation from a centralized model and with fixed tariffs to a liberalized model, where the energy is commercialized and the price is established in the market.

The royal decree 54/1997 of the electric sector, which objective is to guarantee the energy supply and guarantee quality of supply at minimum cost, boosted the liberalization of the electric sector in Spain. This law eliminated the idea that the electric supply is a public service, and introduced mechanisms of free market in some sectors of the energy chain (generation, distribution and retailing), that before belonged to the state.

Spanish government considered adopting a self-consumption law in order to regulate the electricity sector. It is recompiled in a royal decree, the RD 900/2015 [17] on 10th October 2015, which regulates self-consumption in a way that every person who decides to self-consume and is connected to the grid has to pay an extra tax.

The microgrid is based on self-consumption and it is connected to the grid as a big consumer in tariff 6.1A (high voltage from1 kV to 36 kV). The RD 900/2015 establishes different important points that have to be considered:

- No limitation for contracted power but power installed has to be below the contracted power.
- It is not mandatory that consumer and producer is the same person (both natural and legal).
- The generation plant has to be registered as electric production installation.
- It determines a payment of 7% from market price due to generation tax for electric generators.
- It will be necessary to request a supply point to the distribution company.

The self-consumption tax varies depending on the contracted tariff and power installed, the aim of which is to cover the charges associated with the costs of the electrical system and the charges “for other services” of the system, and government decided to include them in a First Transitory Provision applied in both fix (power) and variable (energy) terms.

In general there is a lack of legislation in order to regulate microgrids and storage system, but in this study it is considered that they could act in the market how regulated players. The microgrid, due to its small size is considered as a *price-taker* that means that it will not influence the price in the market and no taxation is considered.

Power price

In this thesis two types of contracts are considered: 6.1 and 2.0.

TARIFF 6.1

The type of contract is the 6.1, used by large consumers. The contracted power has to be higher than 450 kW and the rated voltage has to be included between 1 and 30 kV. In this tariff there are six different time periods, and there is a different cost of energy and power for each one of them. The prices have been taken from a real bill of GAS NATURAL FENOSA, attached in the section annex.

	Power [€/kW*month]	Energy [€/kWh]
P1	3.2616	0.136
P2	1.6322	0.115
P3	1.1945	0.106
P4	1.1945	0.091
P5	1.1945	0.085
P6	0.5450	0.072

Figure 4.5 Prices tariff 6.0

Time periods are different depending on the hour and month in which the energy is consumed. In figure there are represented the different time periods during the year.

Horas	0-8	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Enero	P6	P2	P2	P1	P1	P1	P2	P2	P2	P2	P2	P1	P1	P1	P2	P2	P2
Febrero	P6	P2	P2	P1	P1	P1	P2	P2	P2	P2	P2	P1	P1	P1	P2	P2	P2
Marzo	P6	P4	P4	P4	P4	P4	P4	P4	P4	P3	P3	P3	P3	P3	P3	P4	P4
Abril	P6	P5	P5	P5	P5	P5	P5	P5	P5	P5	P5	P5	P5	P5	P5	P5	P5
Mayo	P6	P5	P5	P5	P5	P5	P5	P5	P5	P5	P5	P5	P5	P5	P5	P5	P5
1-15 Junio	P6	P4	P3	P3	P3	P3	P3	P3	P4	P4	P4	P4	P4	P4	P4	P4	P4
16-30 Junio	P6	P2	P2	P2	P1	P1	P1	P1	P1	P1	P1	P1	P2	P2	P2	P2	P2
Julio	P6	P2	P2	P2	P1	P1	P1	P1	P1	P1	P1	P1	P2	P2	P2	P2	P2
Agosto	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6
Septiembre	P6	P4	P3	P3	P3	P3	P3	P3	P4	P4	P4	P4	P4	P4	P4	P4	P4
Octubre	P6	P5	P5	P5	P5	P5	P5	P5	P5	P5	P5	P5	P5	P5	P5	P5	P5
Noviembre	P6	P4	P4	P4	P4	P4	P4	P4	P4	P3	P3	P3	P3	P3	P3	P4	P4
Diciembre	P6	P2	P2	P1	P1	P1	P2	P2	P2	P2	P2	P1	P1	P1	P2	P2	P2

Figure 4.6 Time periods tariff 6.0

TARIFF 2.0

Consumers can contract a tariff 2.0 if their contracted power is lower than 10 kW. There are 3 types of tariffs depending on the number of contracted periods. 2.0A tariff is based on the same price for 24 hours, 2.0DHA has 2 periods and 2.0DHS is classified in 3 periods. After determining the consumption in each hour of the day, it is concluded that tariff 2.0 is the one with favourable prices.

2.0 is a flat tariff, it means that the energy price is the same for all the day and there is a fixed price for the contracted power. The price utilized in this study are taken from Endesa web page. The tariff contracted is ONE_{LUZ} and the price for the electricity is 0.123826 €/Kwh, while the price for the contracted power is 3.170285 €/Kw*month [11].

In addition to the electricity price, it is also considered price for the oil saved using electrical vehicles instead of conventional vehicles. In the GAMS code it is necessary to give a value to the electricity used by electrical vehicles (assumed to be the 20 percent of the battery capacity for simplicity). So, considering that the price for the oil in the Spanish market is about 1.3 €/l [12] and that electrical vehicles can do 100 Km with 16 KWh of energy and that conventional vehicles can run 100 Km with 7 litre of oil, with a simple conversion it is possible to say that each kWh used by electrical vehicles for transportation has a value of 0.568 €.

Additional taxes

It should be applied the electricity tax to the energy and power cost, the electricity tax of 5.11%, and the VAT, some 21% of energy (active and reactive) and power cost.

Price of sell

The hourly price of sell of the electricity have been taken from the OMIE web site, using data of 2016. [20]

5. RESULTS

In this section the results of the study will be presented. How explained in the section “Methodology”, due to computational problems, the simulations have been done assuming that the weather of a month will be repeated for the next twenty years. Of course, that is an absurd and unrealistic situation, but it could be interesting in order to detect the importance of the clime on the total costs of the system and on the type of technologies used. So there will be highlighted the importance of the location (resources) in the construction of a microgrid, and also the impossibility to find a general method in order to size the equipment without have a perfect knowledge about weather, market price etc...

After that, also a sensitivity analysis about technologies used is performed, in order to check the importance to take in consideration various type of systems. Finally, there will be performed and analysed the optimal scheduling of the system under different conditions.

The computation time in all scenarios is trivial and very variable.

i. Weather’s sensitivity analysis

A comparison between the optimal size of the system depending to the available natural resources (wind and sun) is going to be performed.

A resume about the principal difference in the share of costs, production from different sources and energy bought and sell from and to the grid is shown in table I. On the left, it is represented, in order, the investment needed for the photovoltaic, the batteries, wind turbine, the power contracted with the distribution operator and for electrical vehicles; it is also represented the production from photovoltaic, wind turbines, grid, and the energy generated by EV[1].

A common fact between all the scenarios analysed is that batteries are not viable at all. This is due to the high cost of the technology, and also to the fact that electrical vehicles can do the same function of the batteries when plugged to the grid.

[1]Energy generated by EV means the energy discharged by the batteries of the EV, the same logic is used for the energy demanded, that represent the energy used to charge the batteries of the EV.

Table 5.1 Resume sensitivity analysis weather. All the values have been divided by 10^6.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Ago	Sep	Oct	Nov	Dec
IN PV [€]	0.521	0.716	1.13	1.18	1.30	1.29	1.39	1.40	1.24	1.20	1.16	0.22
IN BAT [€]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
IN WP [€]	0.238	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.505
IN GRID [€]	0.487	0.483	0.458	0.468	0.459	0.473	0.445	0.351	0.432	0.440	0.423	0.460
INEV [€]	0.565	0.587	0.538	0.538	0.538	0.538	0.538	0.538	0.538	0.538	0.538	0.562
PROD PV [Wh]	55	69.6	145	161	179	178	216	211	168	153	119	20.2
PROD BAT [Wh]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
PROD WP [Wh]	24.9	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	52.6
PROD GR [Wh]	225	208	177	159	153	159	137	130	170	174	194	228
PROD EV [Wh]	26.4	24.7	25.1	27.2	25.1	25.1	25.1	25.1	27.2	25.1	25.1	25.7
DEM BAT [Wh]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
DEM GR [Wh]	10.8	12.2	27.9	26.1	37.8	42.5	58.8	47.4	43.7	33.2	19.1	67.4
LOAD [Wh]	293	293	293	293	293	293	293	293	293	293	293	293

DEM EV [Wh]	27.9	26.1	26.6	28.8	26.6	26.6	26.6	26.9	28.8	26.6	26.6	27.1
CG [€]	2.33	2.15	1.78	1.57	1.52	1.59	1.33	1.26	1.70	1.76	1.99	2.40
GG [€]	0.044	0.050	0.113	0.104	0.138	0.159	0.231	0.182	0.170	0.135	0.080	0.026
GO [€]	0.058	0.060	0.053	0.059	0.053	0.053	0.053	0.053	0.059	0.053	0.053	0.057
BILL [€]	3.47	3.46	3.22	3.07	3.11	3.21	2.91	2.80	3.15	3.24	3.45	3.49

Also wind turbines in the project are not viable in most of scenarios, they would be viable just during December and January. This because irradiation during these months is so low, so the investment and the production from PV panels, is substituted in part by wind turbines. One of the factors that have influenced the low penetration of wind turbines is the high cost of the technology, but also the location selected, which is a zone where the wind blows very slowly for the major part of the year.

A technology that has a quite constant number of units in the different scenarios is EVs. It can be seen that the majority of the energy flowing in EV is for energy storage purposes and not for transportation. It is possible to appreciate this fact seeing differences between energy used during the phase of charge and the energy used in phase of discharge that is very little. This means that the energy used during transportation is so low in respect to the energy passed through the vehicle. Also the gains due to oil saving for the not usage of conventional vehicles is very low in respect to the voices of cost for EV (10 times lower). This means that EVs are rentable just in the case in which there is a strong usage of the vehicles during the day. In other cases it needs incentives or has to perform other services.

In the two scenarios in which there is an investment for the wind turbine, optimal investment in photovoltaic is lower, and it is also appreciable that the production from PV is not proportional to the quantity of panels installed, here the dependency with irradiation is very strong.

In Figure 5.1 and 5.2 it is possible to appreciate the value of the investment for PV panels, that include all the costs for the installation (capital cost and maintenance), and of the production for each month.

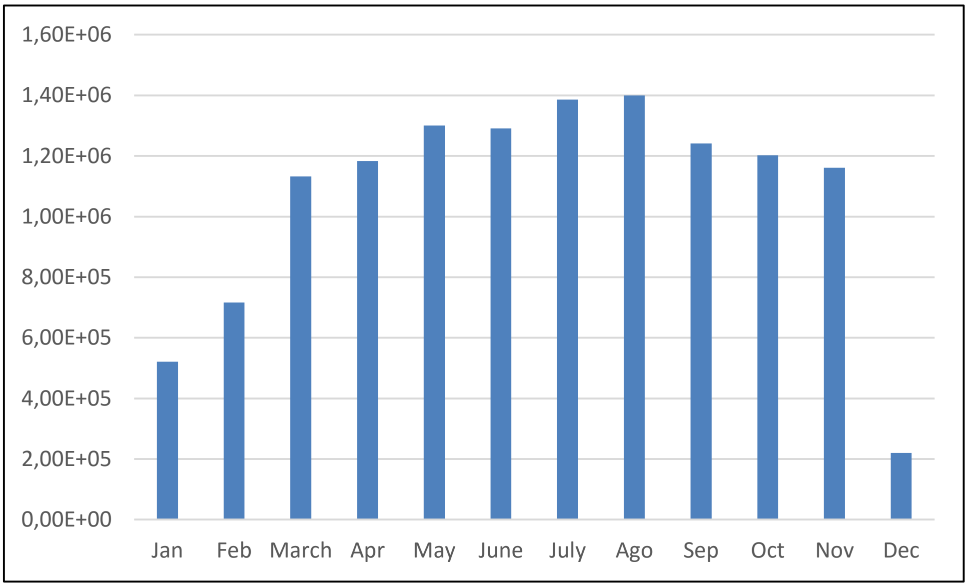

Figure 5.1 Investment PV for each month [€]

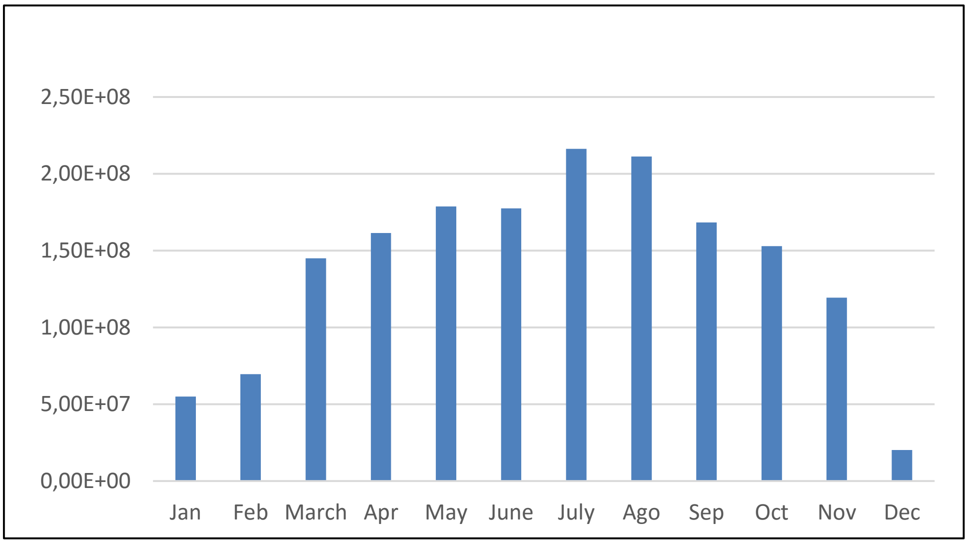

Figure 5.2 Production from PV for each month [kWh]

It interesting that the energy bought from the grid is inversely proportional in respect to the energy produced by PV. This because it is ever preferable the self-consumption in respect to the participation in the energy market.

This is due to the energy price of sell and purchase, the price of sell is very much higher than the price of purchase, so, when it is possible, it is ever preferable to use the energy produced at the same time of the production. If it is not possible, store that energy and it when is needed, or, as last option, to store that energy and sell it when the price in the market is higher.

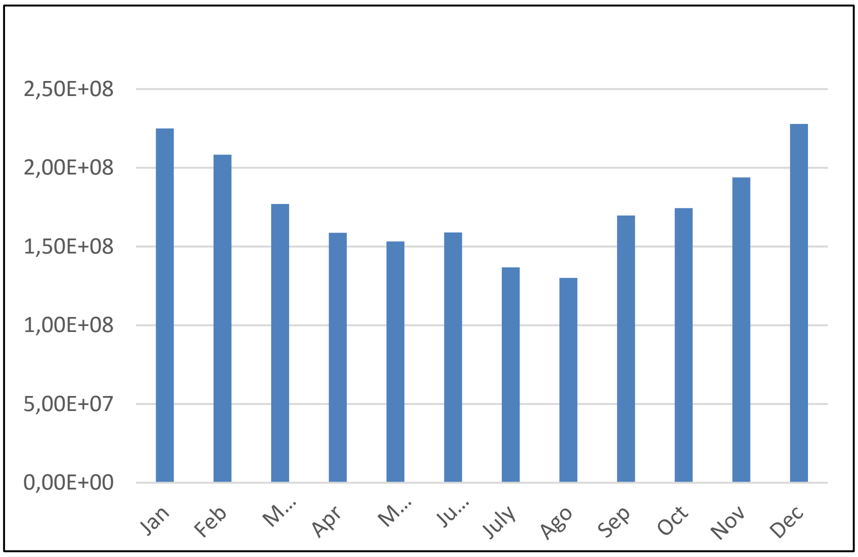

Figure 5.3 Energy bought from the grid for each month [kWh]

Analysing the bill, when bill means the total expenditures of the system, we can note that it follows quite the same trend of the quantity of energy bought from the grid, also if it is more shaved.

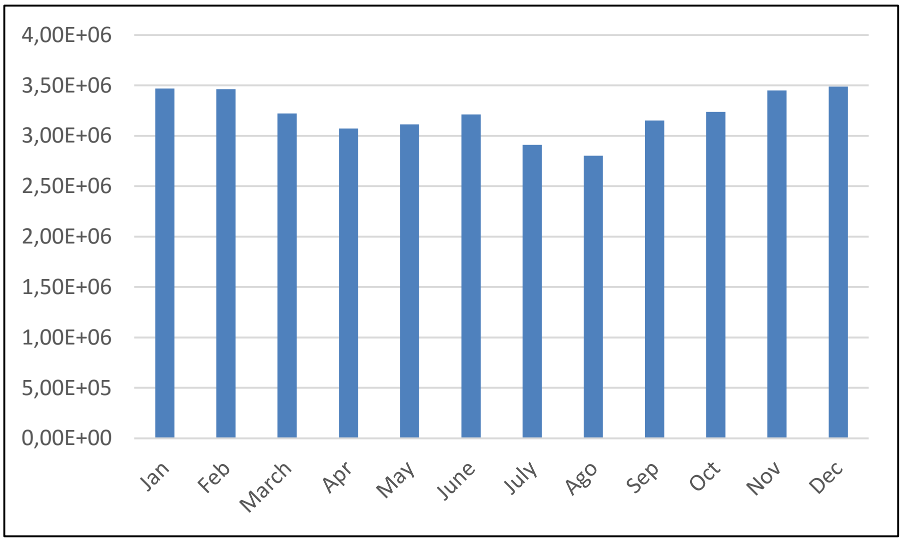

Figure 5.4 Bill for different months [€]

This because the major expenditure for the system is ever the grid, in particular the energy bought from the grid, and in a littlest part the part due to the contracted power. It is important to highlight that this share of cost between energy and power is different from the normal share of cost that we have in a bill.

In this case, all the demand has been aggregated, so the energy and the power is cheaper than the sum of the bills that the consumers would have with a normal tariff. Furthermore, the power contracted has been optimized, while usually consumers haven't the tools and the awareness to optimize the retailing of the energy. The following graph just compare the costs in the bill in the two different base cases (aggregated tariff vs normal tariff).

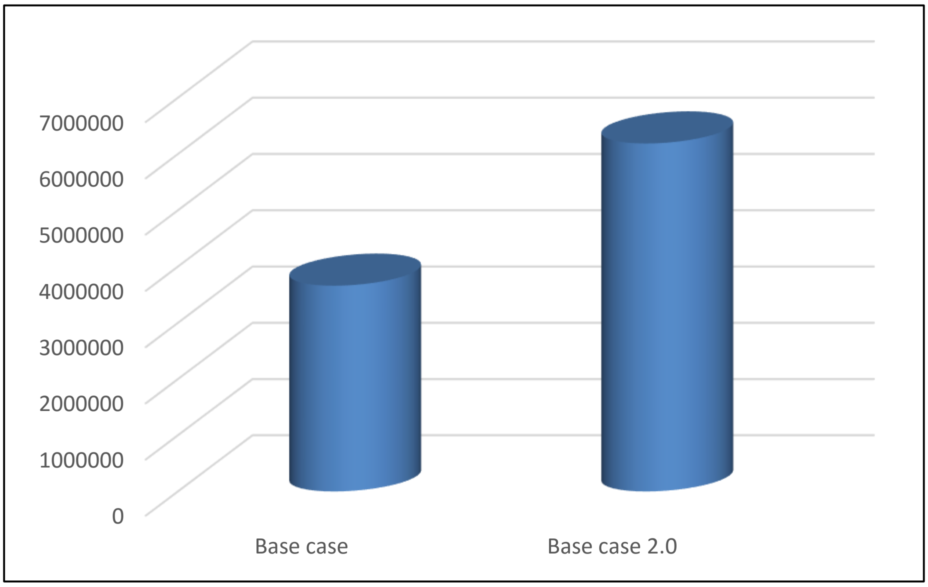

Figure 5.5 Comparison between aggregated tariff vs. multiple tariff [€]

However, also if the final amount of the bill is so similar, the share of costs is so different each month, the share of cost for three typical months is going to be analysed, and it is represented in figure 5.6, 5.7 and 5.8 respectively for the months of December, March and August. In the following sections also the difference in the scheduling of the system for these three months is going to be analysed.

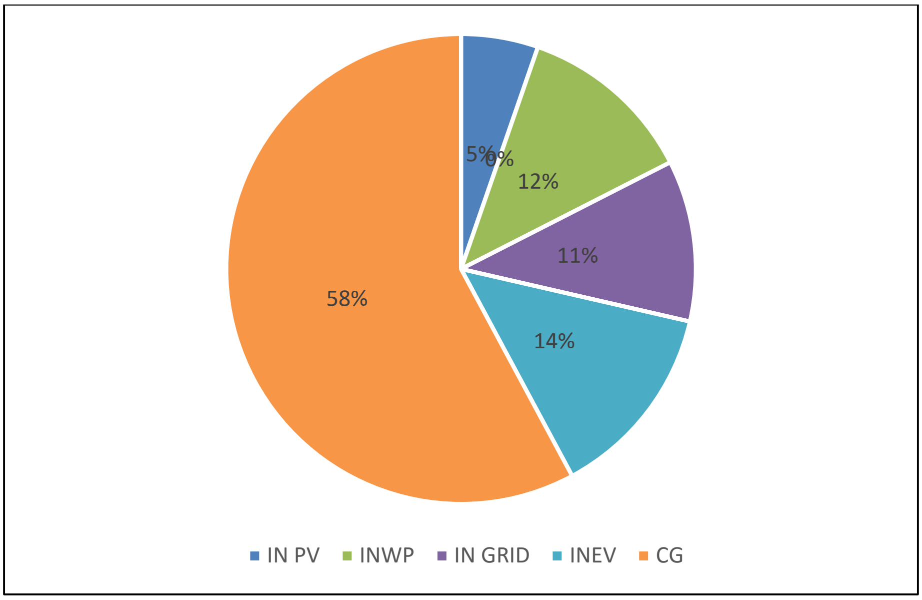

Figure 5.6 Share of costs in December

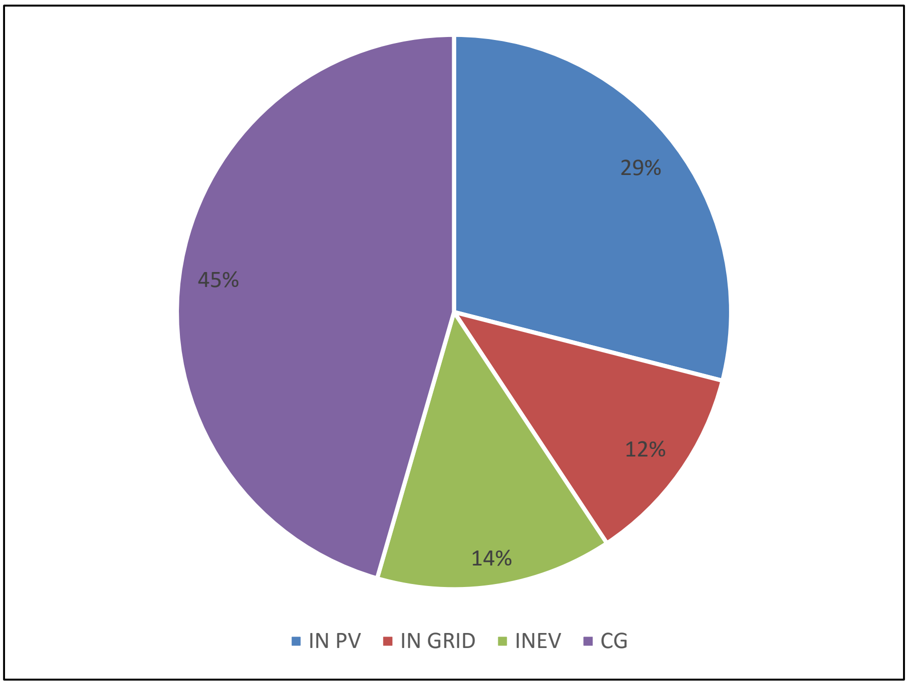

Figure 5.7 Share of costs in March

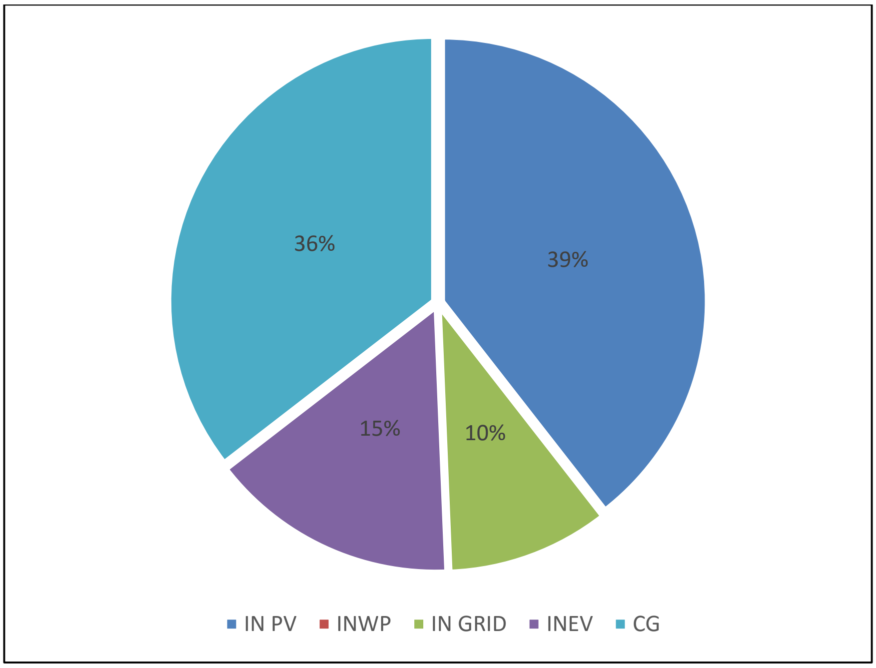

Figure 5.8 Share of costs in August

The costs due to the grid decreases with seasons with a higher insolation: in December the total costs of the grid account the 72 % of total costs, in March the percentage decrease to 59 % and in August it falls to 46 %. This means also that selecting a location with higher irradiation the system will be less dependent to the grid, so it could be possible to stay disconnected from the grid with reasonable costs. One of the simulation was for an isolated system, the program couldn't find a solution, because one of the constraints was to supply ever the load. Maybe using a dispatchable load it could be easier to meet the load at each hour and reach the total independency from the grid.

In percentage the investment for EV is constant, and equal to 15 percent of the total costs, while the investment due to photovoltaic decrease from 39 % in August to 5 % in December.

ii. Technology's sensitivity analysis

In this section it will be performed a comparison of total costs and share of costs during twenty years of life of the system with different technologies. The month analysed is March, this election has been done in order to not influence the results taking in to account a very sunny or a very cloudy month.

The cases studied are 10: base case with tariff 6.0, base case with tariff 2.0, just PV and grid, PV with batteries and grid, just wind power, wind power with batteries and grid, wind power with PV, batteries and grid, all the technologies (wind power, PV, batteries, EV and grid) with tariff 6.0, all the technologies (wind power, PV, batteries, EV and grid) with tariff 2.0, and all technologies with tariff 6.0 but with a double cost of the power contracted. In table II a resume of the results presented.

One of the results that can be assumed seeing the table is that, obviously, as more technologies are involved in the decisions more the total costs go down.

Also a quite surprising result is that batteries in any scenario are viable. This means that the technology yet is not competitive in the market, and that has to be developed in order to low its price.

Also wind power is not really competitive and it is viable just when there are no other options to produce energy from renewable sources or when there is the possibility to use the EV. This is due also to the fact that EV are plugged to the grid during night when, usually the wind blows faster. For this reasons, different scenarios are equal and further comparisons can be done in a reduced range of results.

Table 5.2 Resume sensitivity analysis technologies. All the values have been divided by 10^6

	Base case 6.0	PV	PV+ bat	Wind	Wind + bat	Wind+ PV+ bat	Wind+PV + EV	double cost power	Base case 2.0	March w 2.0
IN PV [€]	0.00	1.13	1.13	0.00	0.00	1.13	1.13	1.16	0.00	1.27
IN BAT [€]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
IN WP [€]	0.00	0.00	0.00	0.475	0.475	0.00	0.00	0.00	0.00	0.792
IN GRID [€]	0.519	0.458	0.458	0.504	0.504	0.458	0.458	0.914	0.590	0.519
INEV [€]	0.00	0.00	0.00	0.00	0.00	0.00	0.538	0.538	0.00	0.302
PROD PV [Wh]	0.00	145	145	0.00	0.00	145	145	149	0.00	161

PROD BAT [Wh]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
PROD WP [Wh]	0.00	0.00	0.00	48.8	48.8	0.00	0.00	0.00	0.00	79.4
PROD GR [Wh]	293	172	172	246	246	172	177	175	293	119
PROD EV [Wh]	0.00	0.00	0.00	0.00	0.00	0.00	25.1	25.1	0.00	6.48
DEM BAT [Wh]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
DEM GR [Wh]	0.00	24.5	24.5	2.20	2.20	24.5	27.9	29.7	0.00	68.3
LOAD [Wh]	293	293	293	293	293	293	293	293	293	293
DEM EV [Wh]	0.00	0.00	0.00	0.00	0.00	0.00	26.6	26.6	0.00	5.41
CG [€]	3.20	1.83	1.83	2.69	2.69	1.83	1.78	1.76	5.60	2.52
GG [€]	0.00	0.0995	0.0995	0.0093	0.0093	0.099	0.113	0.120	0.00	1.23
GO [€]	0.00	0.00	0.00	0.00	0.00	0.00	0.536	0.536	0.00	0.300
BILL [€]	3.66	3.29	3.29	3.61	3.61	3.29	3.22	3.68	6.19	4.80

It is curios that the addition of about 50 EVs doesn’t increase the optimal number of panels to be installed on the roof and neither the power contracted to the grid, but just the energy bought from the grid. The explanation for the stability in the contracted power is, how explained before, that EVs are plugged to the microgrid during the night, when the load is lower, so energy can be bought during valley hours.

Savings are about 40 percent of the initial costs and it is the most attractive investment that an organization could do because it hasn’t no initial cost, a part of a transformer and some private energy meter in order to compute the real consumption of each consumer. However, due to the lack of legislation in some countries, how Spain, it could be impossible to aggregate the demand in an only one contract.

Also the scenario in which cost of power is double than power cost of the first case has been analysed. The intention is to check the influence of the power's price in the decisions taking, since the trend of the last years is to increase, while the cost of energy is going to be lower and lower. On one side in the last years the energy cost is lowing thanks to renewable energies which don't have operational costs, so they can offer their product in to the market at a null value. On the other side, the costs due to congestions' management into the lines is getting ever more expensive. Likely, the Transport System Operators and Distribution System Operator will have, in the next period, to decide if invest in a reinforcement of the grid in order to face at peak load. An alternative would be to incentive Demand-Side Management, allowing to shift the load from peak hours to valley hours and reduce loses in the grid through a distributed generation.

In this case the total bill suffer an appreciable difference in the price, equal to the 12 percent of the total costs. Also, the costs are shared in a different way. Investment in photovoltaic are higher in the case with an higher price of power and the total cost due to the grid are a 13 percent higher, while in absolute value the optimal number of electrical vehicles is the same, how can be seen in the following graphs. Of big interest is the fact that with a double cost of power, the optimal contracted power in this scenario is the same than in the scenario with the actual cost of power.

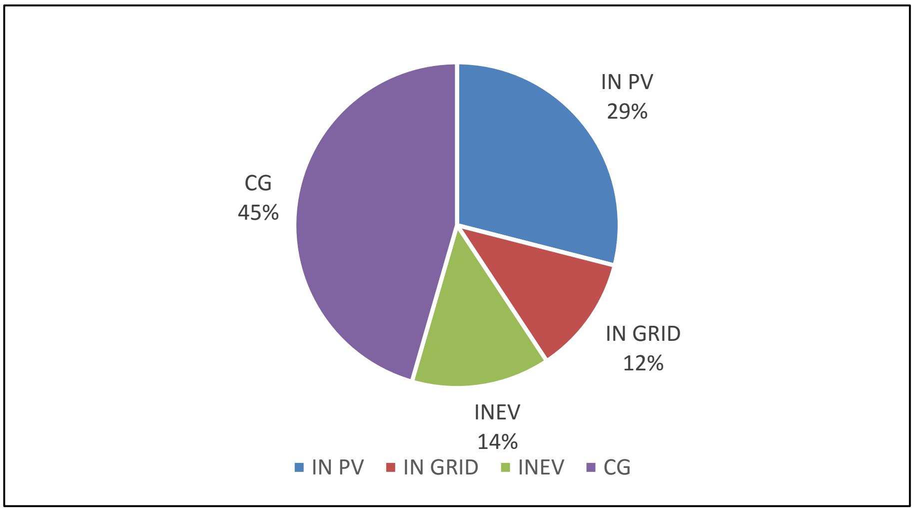

Figure 5.9 Share of costs considering all technologies

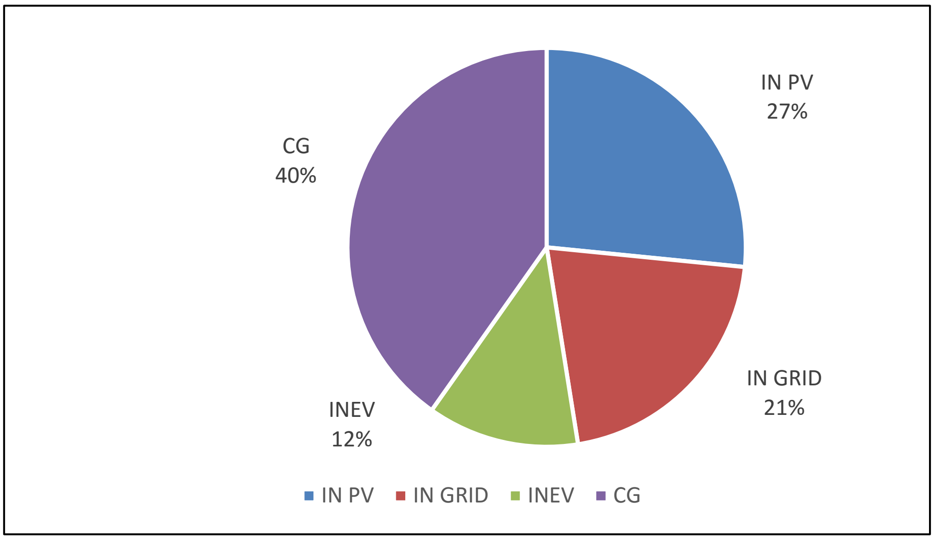

Figure 5.10 Share of costs with double price of the contracted power

An interesting comparison is that between the scenario in which it is considered how unique resource wind power, and the scenario in which just the possibility to install photovoltaic is taken in to account. The total bill in the second scenario is clearly lower respect to the first, roughly a 9 % of the expenditure can be saved, taking into account the use of solar power instead than wind power in a location with the conditions considered in this study (Girona's Airport in March). The capital cost of the scenario with solar panels is two times in respect to the investment in the other scenario, because more kW of renewable energies are installed. In Figure 5.11 and 5.12 it is represented the share of costs in the two cases.

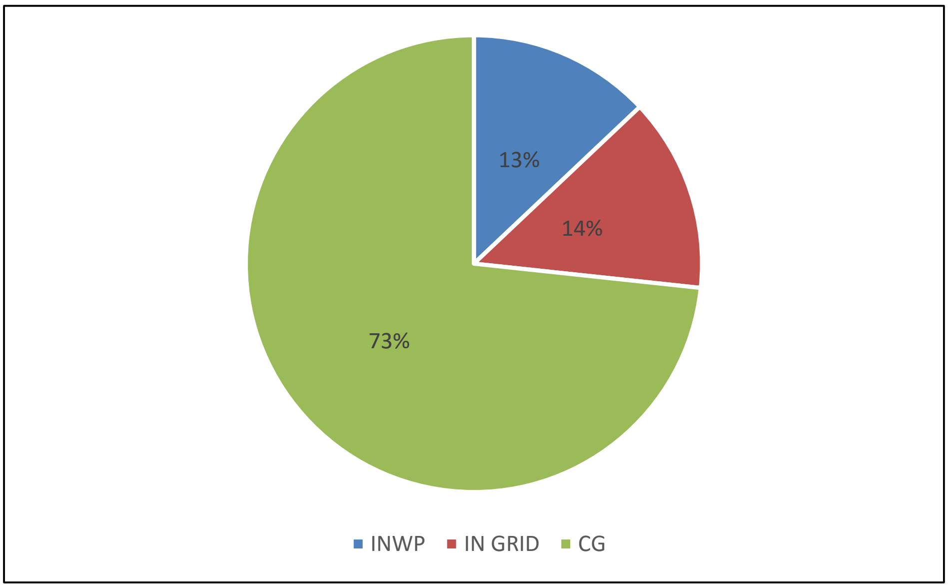

Figure 5.11 Share of costs considering just wind power

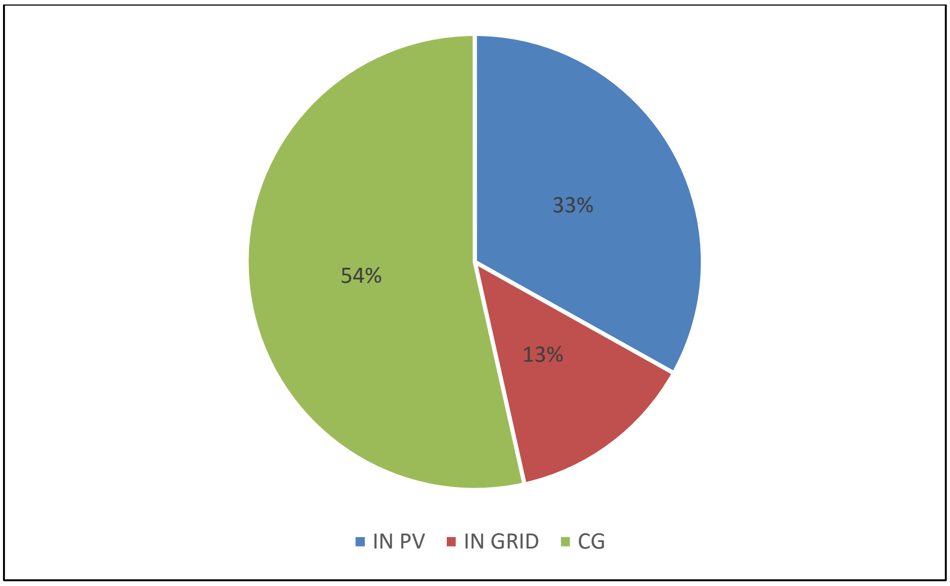

Figure 5.12 Share of costs considering just PV panels

A common fact in the two scenarios is that in none of the two batteries are considered a viable solutions, due to its high cost. Surely, if there would have been installed batteries, the peak of power bought from the grid would have been lower. It is necessary to highlight that the power contracted in the grid (peak of demand from the grid), has a lower value in the case with PV panels.

Also the total energy bought from the grid is 1.5 times higher in the case with wind power than in the case with PV panels. These two evidences are interesting thinking to the important role that microgrids could have in future linked to a reduction of the peak load. In a weather as Girona, PV will have a most important weight than wind power in that service, so incentives should be focused on solar power.

On the other side, energy sold to the grid in the solar-based scenario is higher. In the case of future great expansion of the microgrids, this could create problems that will have to be faced with storage systems and with reinforcements of the grid to allow a bi-directional flow of the power.

It is interesting to compare the share of costs and gains in the case with PV panels and that with PV + EV. The number of panels installed is the same, so a higher load, due to EVs doesn't bring to a higher investment in renewables energies, but just to more energy bought from the grid.

In addition, how exposed in table II, just economic savings from oil due to the usage of EVs, wouldn't justify the investment, because savings are lower than the investment. The investment is justified just in the case in which they can be used as batteries, so buying energy when it is cheaper and storing electricity produced by solar panels instead to sell the energy to the grid. In a real case it is necessary to evaluate the possibility to use these EV batteries in this way, taking into account the costs for the usage of batteries and the reduction in its time-life.

iii. Scheduling of the system in different scenarios

In this section there will be described the optimal scheduling of the system with different availability of resources (wind and sun). The three months analyzed will be December, March and August. After that, also the specific behavior of the electrical vehicle's battery will be analyzed.

The first month analyzed will be December, in which there are 228 kW of PV panels and 502 kW of wind turbines and 1.348 MWh of EV battery's capacity.

Results in GAMS are not easy to comment at all, because there are different parameters that can influence the results, so it is convenient to analyze the trend for the different values for short time step. In the left vertical axis of figure 5.13 it is represented the evolution of the load, PV and wind generation, purchases and sales from and to the grid and the use of the batteries of electrical vehicles. The aim of the study is to find the optimal utilization of the batteries in order to manage purchases and sales from and to the grid when the system is sized.

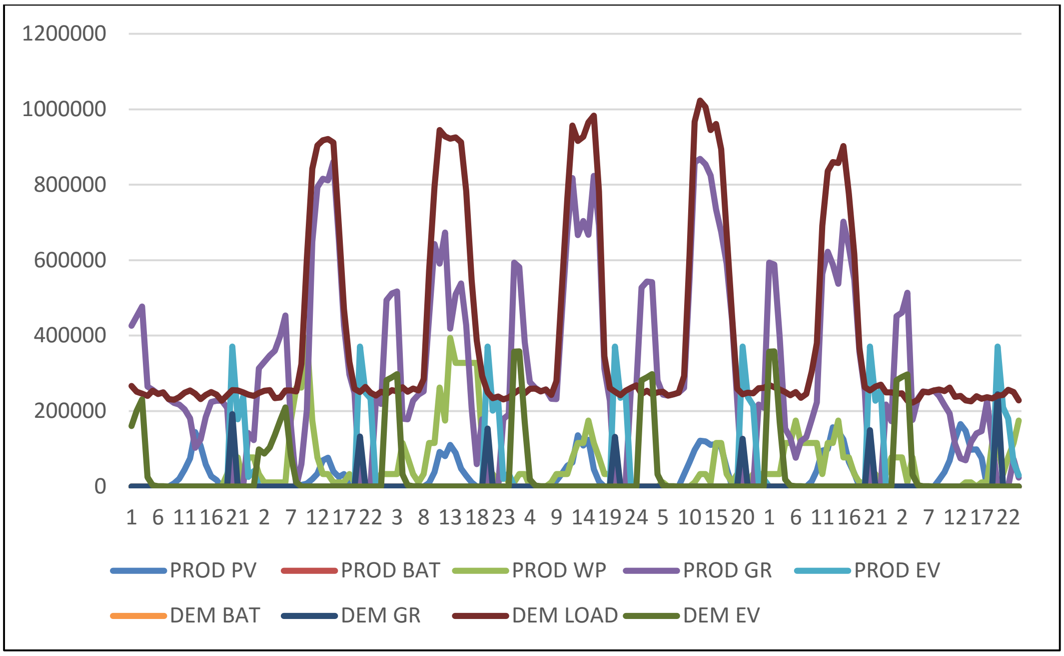

Figure 5.13 Scheduling of the system during a week in December [Wh vs hour]

The first day analysed in is during week-end, a Sunday, so the load is low. It is possible to appreciate that during night energy is bought from the grid in order to charge batteries, while during day, when there is a little bit of production form solar PV, energy bought from the grid is lower than the load. From 20:00 to midnight of the Sunday, energy stored by EV is used to supply the load and, in part, is sold to the grid, when it is more expensive.

During the second day, on Monday, from midnight to 8:00 a.m. (valley hours), energy bought from the grid is more than the energy needed by the load, because a part is used to charge EVs' batteries. During day the load is quite completely supplied by the grid, and in part from wind and solar power. From 8:00 pm to midnight EVs' batteries supply the load and sell its energy to the grid, while during the night the grid supplies the load and charges batteries.

This is the typical scheme during all days, depending to the production from renewables the grid can be used more or less, but during the day there's ever a purchase of energy from the grid, than from 8:00 pm to midnight EVs are used to supply the load and during the night they are charged by the grid.

In figure 5.14 it is represented the behaviour of EVs' batteries during the week.

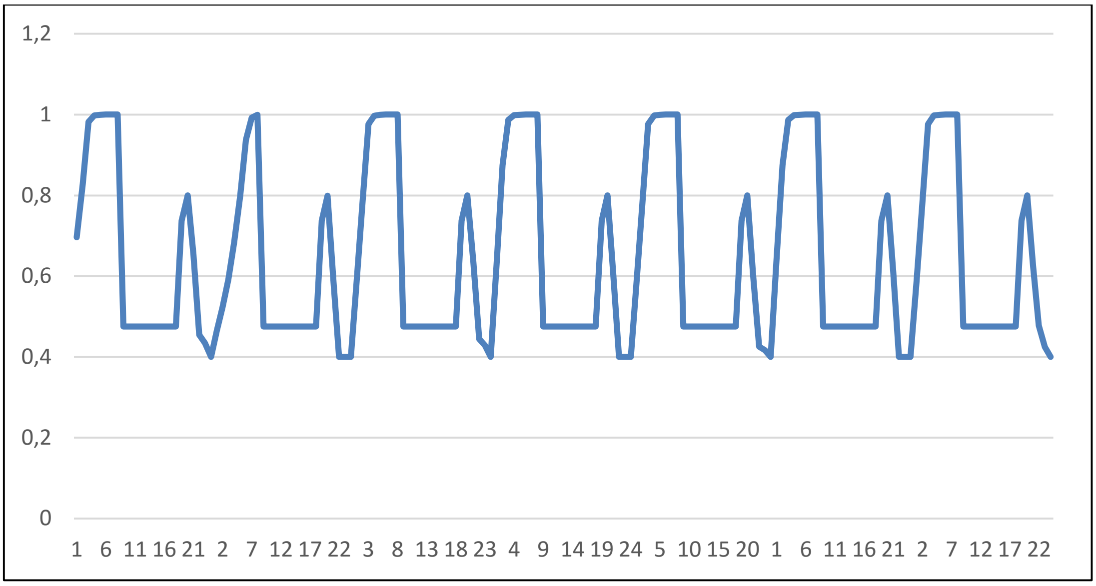

Figure 5.14 SOC EV's batteries during a week in December

How can be seen, state of charge of batteries is ever between 0.4 and 1, so it respects the range allowed for these type of batteries. The big step at hour 8 represents all the energy used from 8:00 to 20:00 for transportation. During the night it is ever charged until the top, while it reaches the minimum level allowed at midnight. The same scheme is repeated in all days.

The next month analysed is March, the system is formed by 1.17 MW of photovoltaic panels and 1.3 MWh of EV batteries capacity.

In Figure 21 it is represented the behaviour of all components of the system during a typical day in March.

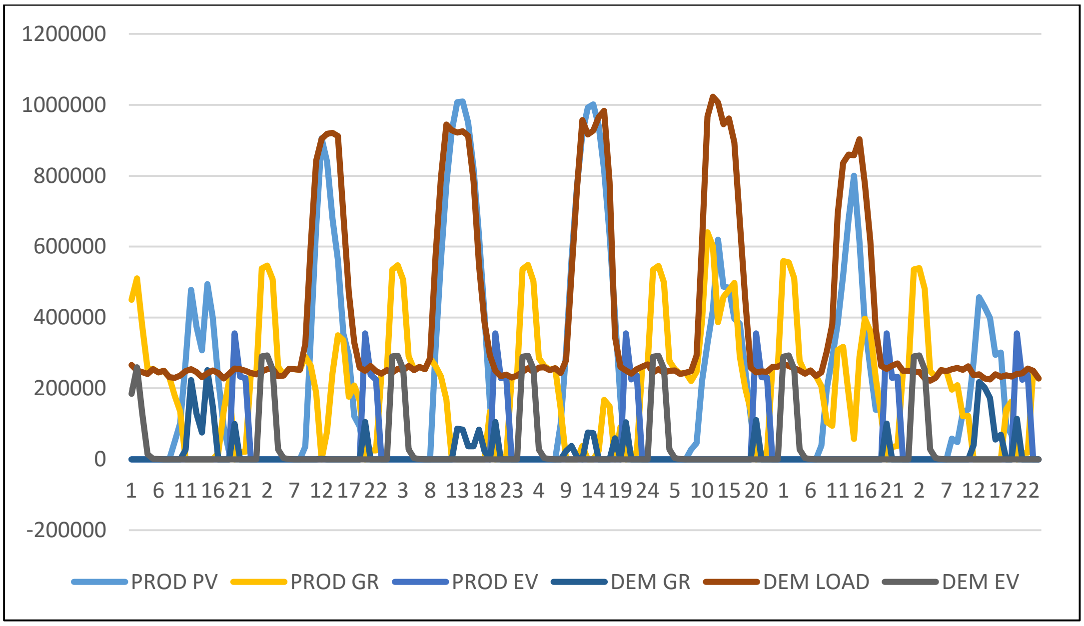

Figure 5.15 Scheduling of the system during a week in March [Wh vs hour]

In this case, production from renewables is clearly higher than during December, so the system has a different behaviour. The focus will be on the differences between this and the first.

The first day is Sunday, so he load is low and flat during the whole day. During the night, energy is bought from the grid in order to charge EVs and supply the load, but during the day production from photovoltaic is higher than the load, so in this case energy is sold to the grid. It is important to highlight that it is sold to the grid because EVs are unplugged, so they can’t be charged, if not it would be preferable to charge batteries instead to sell energy to the grid.

During the second day, production from solar PV is so similar to the demand curve, so the load is supplied by renewable energy and in minor part from the grid. In other days the production from solar PV is higher than the load, so a part of the energy produced is directly sold to the grid.

The graph that represents the SOC of electrical vehicles batteries in March is so similar to the graph that represents the behaviour of EV batteries during December.

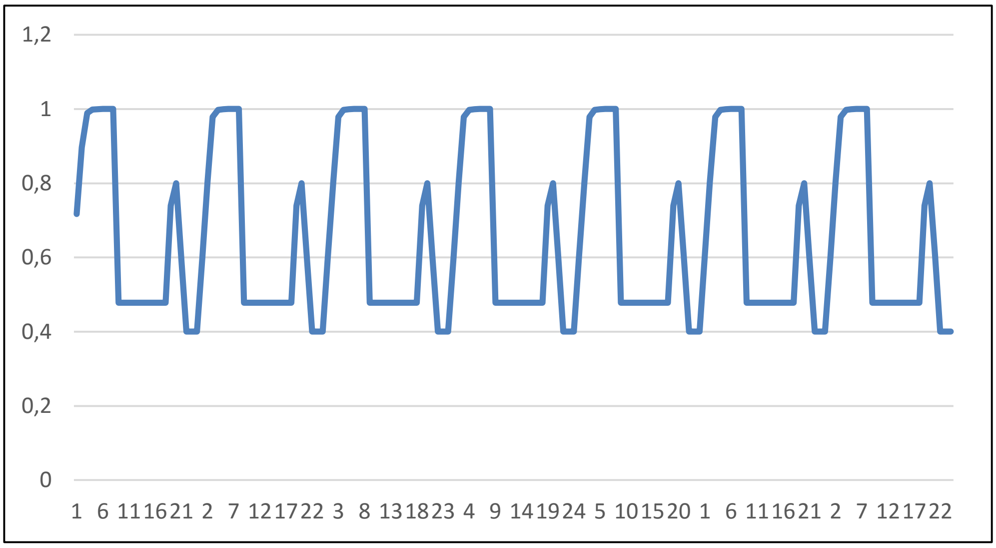

Figure 5.16 SOC EV's batteries during a week in March

The last month analysed is August, PV nominal power is in this case 1.41 GW, and 1.3 MWh of EVs’ batteries capacity.

The optimal scheduling of the system is represented in the following graph.

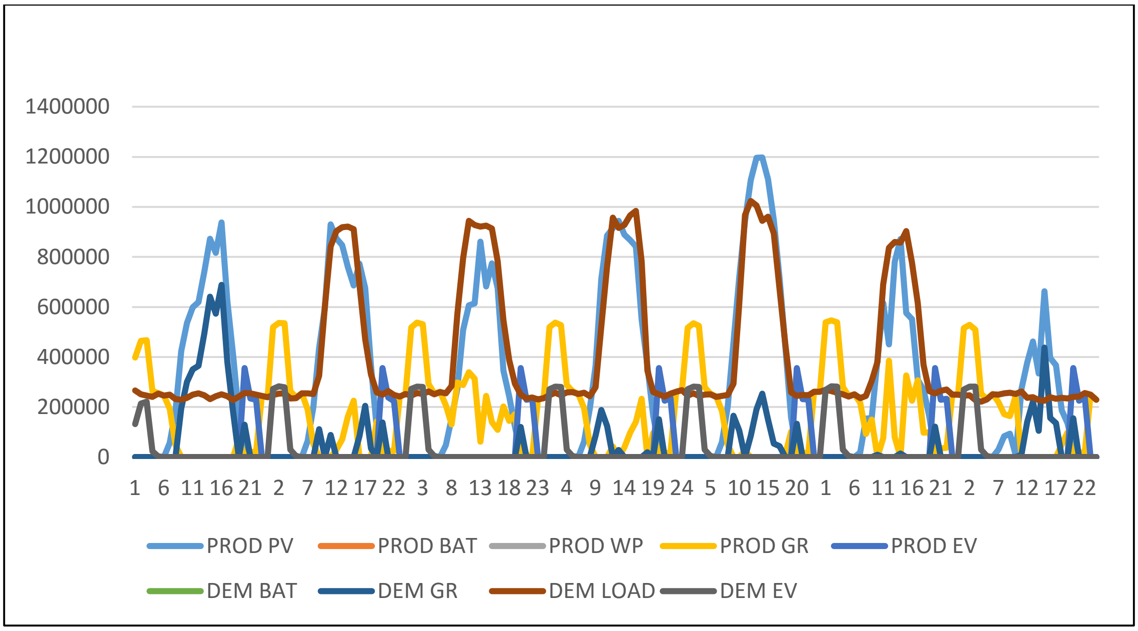

Figure 5.17 Scheduling of the system during a week in August

In order to not bore the reader the pasts behaviour won't be repeated, there is just to highlight that in this case there is a higher production from renewables, which often is bigger than the load. For this reason so much energy is sold to the grid, while less energy is bought and the peak of power is lower. This is reflected in a lower investment due to the grid and lower operational costs of the system.

Also the behaviour of EV is quite similar to the behaviour presented in March.

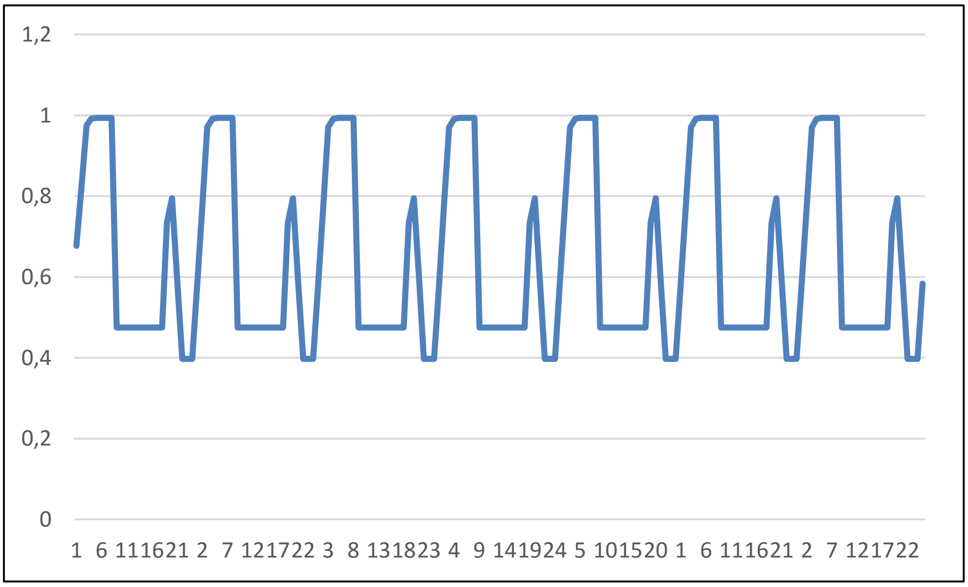

Figure 5.18 SOC EV's batteries during a week in August

6. FURTHER IMPROVMENTS

In this section there will be described some possibilities to continue and improve this project for future researcher in order to keep the work ever more realistic eliminating some assumptions and in order to realize a more complete job.

In order to size a real system it will be fundamental to use longer historical data. Due to the hourly, seasonally and yearly variability of resources like wind and sun it is very important to take into account data series of at least five year. In this way data will be more realistic because using data of just one month could bring huge errors of planning.

Furthermore it will be very important to do a forecast about the load in the following years, taking historical data as a base. This because, in residential and yet more in industrial environments, the type of production and the technologies used can change so much the demand curve. For example, passing from a fuel-based heating to an electrical heating will increase the consumption, while change conventional lights for LED lights will decrease it.

For this reason, before to size a microgrid is very important to plan future productions and consumptions. In addition it will be necessary to do deep studies about the future variation in the price of the electricity, of the contracted power and of the natural gas, but also about future costs of equipment's maintenance and about replacement cost of batteries. Surely, this type of forecasts are very difficult to do because they depend on different non predictable factors, e.g. incentives, political decisions, development of the technology etc… For this reason, an option could be to perform different possible scenarios, and in base at the probability of each scenario, select the better option.

Another R&D option is to develop a business model for this type of system and to decide the way to share costs and gains between single users. It could be interesting to check opportunities for an external company to decide to invest in the project, taking a percentage of the total savings or offering a fixed tariff for the clients. However, it could be better for the users to share the investment and have a total independence from external entities.

Important improvements can be developed for the scheduling of the system. Have a weather station in the system in order to predict the production from renewable energy sources in a real time and for a longer time horizon will be needed [18]; a price-forecast program will be necessary in order to optimize the system scheduling [19] and a forecast of the load will have to be performed too.

Also a shiftable load could be introduced in order to have a grade of free on the control of the consumption. In [20] there is described one of the techniques used to forecast the consumption. In this way there will be introduced another variable, with its constraints, that will give a contribution in the reduction of the bill, in the part of the contracted power and in the increase of the self-consumed power.

This type of prediction should have a time-horizon of 3-5 days but, in order to adjust the errors in the predictions, a short-term scheduling with 15 minutes samples will be needed. In this case, it could be introduced the participation of the microgrid in the secondary market, in order to offer ancillary services to the grid. In this case, how exposed in [21], the savings could be exponentially greater than the actuals.

Finally, in order to pass from the software to the hardware, a program as Arduino should be implemented in order to simulate the behaviour in a real system.

7. CONCLUSIONS

Microgrids will have a fundamental role in the smart grid of the future, offering great advantages to its users from an environmental and economic point of view. They will reduce emissions of pollutant gases thanks to the distributed generation from renewable sources and a decentralized production that will bring to a reduction of total grid's losses. The principal contribution of the paper is to have contributed to implement a tool in order to size in an optimal way a microgrid in general conditions. From an economic point of view, the possibility to can aggregate demand and production and to can manage the load, principally thanks to the use of storage system and electrical vehicles, allow to use over-production in other moments. Of consequence it will be possible to reduce the peak power contracted and to buy electricity when it is cheaper.

The appearance of electrical vehicles in the market, and its future spread will face the grid to an increase in the electric consumption and possible congestions. On the other side electrical vehicles could be an opportunity for the development of the smart grid if used how a storage system at zero cost and could in part substitute the usage of conventional storage systems, which usually are still so much expensive.

In this study it has been highlighted also the importance of the weather conditions in the construction of a microgrid and has been proposed a general method in order to model a microgrid. It has been get out that in the most favourable scenario (weather all the year like August), the microgrid is self-sufficient during the day thanks to solar power and is able sometimes to sell over production to the grid bringing down its overall costs. In percentage the difference in the bill between August and December is about 20 percent, also if the investments needed for the scenario of August are a 35 percent more.

How commented in the section results, it is evident the importance to consider all the technologies available in the market during the project of a microgrid in order to have a reliable project. In addition has been found that just aggregating the demand would bring to tremendous economic savings (the bill would be 40 % lower) without any investment but just changing the contract.

However, due to a lack in the legislation in some countries like Spain it is not possible to aggregate the demand and neither to use storage systems, so these type of systems are not possible. Surely, in the future it will be, European Union is imposing at individual countries to allow the incorporation in the electricity market at aggregated demand and storage systems in order to facilitate the evolution toward a new energetic models, in which consumers will be also producers and will participate in the electricity market modelling their consumptions and productions in base at electricity prices of the day ahead market and the balancing markets.

8. AGRADECIMIENTOS/RINGRAZIAMENTI

Primero, muchas gracias a **Francisco Díaz-González** para haber aceptado mi propuesta de tesis, para haberme ayudado a aprender cómo utilizar GAMS y para contestar a mis interminables preguntas.

Muchas gracias también al personal de IREC, para haberme dado confianza y para permitirme de poder acabar este trabajo durante el primero mes de mi nueva aventura en el doctorado, en particular a **Cristina Corchero**, **José Luis Dominguez** y **Lucia Igualada.**

Gracias también a los profesores del máster para haberme estimulado el interés en el campo de la ingeniería de la energía, y a todos los compañeros de clase para haberme ayudado al principio que no hablaba castellano, en particular a **Roger** que también me ha explicado todo el sistema energético español desde el principio.

Un grande ringraziamento a tutta la mia famiglia che mi ha permesso di fare la esperienza di venire a vivere a Barcellona e sempre mi sopporta nelle mie decisioni.

Non voglio dimenticare anche tutti i miei amici che stanno in Italia per non odiarmi se non mi faccio sentire per tanto tempo, pero sempre ci sono in qualsiasi momento.

Finalment voldria agrair a tothom amq qui he compartit alguna cosa durant aquest dos anys a Barcelona, també la més petita.

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10. ANNEX

Bill 6.1 Gas Natural Fenosa

CONCEPTO	CANTIDAD		MESES	PRECIO UNITARIO	IMPORTE	
TÉRMINO DE POTENCIA P1	1.500,0	kW	1,0	3,261619	4.892,43	Eur
TÉRMINO DE POTENCIA P2	1.500,0	kW	1,0	1,632221	2.448,33	Eur
TÉRMINO DE POTENCIA P3	1.500,0	kW	1,0	1,194515	1.791,77	Eur
TÉRMINO DE POTENCIA P4	1.500,0	kW	1,0	1,194515	1.791,77	Eur
TÉRMINO DE POTENCIA P5	1.500,0	kW	1,0	1,194515	1.791,77	Eur
TÉRMINO DE POTENCIA P6	1.500,0	kW	1,0	0,545015	817,52	Eur
ENERGÍA ACTIVA P1	76.548	kWh		0,106964	8.187,88	Eur
ENERGÍA ACTIVA P2	125.692	kWh		0,090516	11.377,14	Eur

FACTURA Nº

PI16142000035460

PERIODO

01.01.16 - 31.01.16

CONCEPTO	CANTIDAD		MESES	PRECIO UNITARIO	IMPORTE	
Viene de página anterior ...						
ENERGÍA ACTIVA P6	144.389	kWh		0,056379	8.140,51	Eur
COSTE INTERRUMPIBILIDAD					690,92	Eur
IMPUESTO ELÉCTRICO 31.01.2016 - 31.01.2016	41.930,04	Eur		0,0511269632	2.143,76	Eur
ALQUILER DE EQUIPO DE MEDIDA					60,89	Eur